SBS Mitigation with 'Multi-Tone' Amplification – A Theoretical Model

T. Justin Bronder, Iyad Dajani, **Clint M. Zeringue**[1], Craig A. Robin and Thomas M. Shay

Air Force Research Laboratory, High Power Solid State Lasers Branch, Kirtland Air Force Base, NM 87117

A novel technique for mitigating stimulated Brillouin scattering (SBS) in gain fiber through seeding by two master oscillators is extended to three seed signals. This 'multi-tone' amplification uses more than one master oscillator signal where the relatively large frequency separation of the signals (10's of GHz – THz) allows each 'tone' to reach its SBS threshold nearly independently and thus increases the overall nonlinear threshold by a factor of 2 (for two input signals) or 3 (for three inputs) in the amplifier. We report the first theoretical model for such a fiber amplifier system that simultaneously solves for the amplified signal, SBS, and four wave mixing (FWM) intensities. The details of the model and specific results – such as the optimum frequency separation, increase in the SBS threshold, and FWM – are also discussed.

One serious limitation in the peak power from CW narrow linewidth fiber amplifiers is the onset of SBS, the lowest threshold nonlinear effect in these systems. This paper presents theoretical verification of a new technique of 'multi-tone' amplification that predicts an increase in the SBS threshold in a fiber amplifier by approximately 96% and 196% using two and three (respectively) master oscillators if the wavelengths are properly selected. The frequency separation of these separate input 'tones' is large enough (10's of GHz to THz) so that each amplified signal reaches its SBS threshold nearly independently.

This technique is modeled in Mathematica and reduces to a 12x12 system of coupled nonlinear equations. The gain in the fiber is modeled as a two-level system. The pump, the input seeds and their Stokes light, and a total of 4 upper and lower sideband oscillations due to FWM are included. We note that in the case of 'three-tone', FWM can directly transfer power among the seed signals. Due to its numerical and symbolic capabilities, Mathematica is well-suited for this problem. For example, in the case of 'three-tone', there are 128 terms due to FWM; these were generated symbolically in Mathematica and incorporated in the numerical solver. The entire system of equations represents a two point boundary value problem where the seed signals and FWM sidebands are known at the input end of the fiber while the Stokes signals are noise initiated and are known at the output end.

A large mode (25 μm core radius) Nufern Yb-doped fiber was modeled as the gain element in a co-pumped fiber amplifier setup with seed signals near 1068 nm. This model is the first of its kind to incorporate all of the physics in such a fiber amplification scheme. This was necessary as the interplay between the gain, Stokes, and FWM-generated sidebands is essential to fully understanding the benefits and limitations of this particular SBS mitigation technique. Of particular note is the wavelength separation $\Delta\lambda$ of the input master oscillator 'tones'. In the 'two-tone' case, SBS was the predominant limiting nonlinear effect in wavelength separations as small as 0.1 nm, although the amount of power 'lost' to FWM-induced sidebands [for an amplifier operating near the SBS threshold] doubled at a $\Delta\lambda$ of less than 3.0 nm. In 'three-tone' amplification, the FWM effects were more pronounced; the FWM power increased by an order of magnitude between $\Delta\lambda$=3.0 nm and $\Delta\lambda$=2.0 nm and overcame SBS as the lowest-threshold nonlinear effect at $\Delta\lambda$=1.0 nm. Future experimental plans to verify these theoretical findings are discussed and the use of this fiber amplifier system for beam combining applications is considered.

This model was benchmarked against the similar SBS mitigation experiments [1], where two master oscillator seed signals were selected at twice the Brillouin-shift; this ensured that the Stokes signal from the higher frequency seed is effectively depleted through coupling to the lower frequency seed. This experiment showed an improvement in SBS threshold operation of 200%, but with clear FWM effects in the spectrum. Our 'multi-tone' model reproduces these effects and we also show ways to improve the performance of this specific SBS-mitigation scheme and extend it to multi-tones.

[1] Wessels P. et al., Optical. Express. **12**, 4443-4448 (2004)

[1] E-mail: Clint.Zeringue@kirtland.af.mil