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## Tutorial for:

## Designing high power single frequency fiber lasers

Single frequency lasers with narrow linewidth have long coherence length and this is an essential property for many applications in industry and science. One of the applications is remote laser sensing and in particularly laser guide star, where high power narrow linewidth laser at 589nm is required for excitation of sodium atoms [1]. Another important application is coherent beam combining [2], where the power is scaled up by combining several lasers with the diffraction grating.

Extensive research and development of the fiber lasers allowed to substitute solid state lasers for many applications. Fiber lasers have obvious advantages over solid state lasers: stable beam profile at the output and absence of free space optics alignment. Although, the output power of the single frequency fiber laser is limited by the stimulated Brillouin scattering (SBS) [3-4].

Brillouin scattering is an interaction between light and a medium where light is propagating. Incident photon is transformed into scattered photon and acoustic phonon. In fiber the scattered light mainly has a backward direction [3-4]. The scattered light has a frequency downshifted by  $\Omega_{B'}(2\pi)=2nv_{A'}\lambda_{p}$ , where  $v_{A}$  is a velocity of the acoustic wave in an optical fiber,  $\lambda_{p}$  is a wavelength of incident light and *n* is a refractive index of the fiber. At high laser powers the process becomes stimulated and most of the power can be scattered back. In fiber lasers it is a parasitic effect that limits the output power. To estimate the critical power ( $P_{cr}$ ) when the SBS will appear we can use the following formulas [3-4]:

$$g_B P_{\rm cr} L_{\rm eff} / A_{\rm eff} \approx 21 \tag{1}$$

$$g_B(\Omega) = g_p \frac{(\Gamma_B/2)^2}{(\Omega - \Omega_B)^2 + (\Gamma_B/2)^2}$$
(2)

Where  $g_B(\Omega)$  is a Brillouin gain spectrum,  $L_{eff}$  is effective fiber length,  $A_{eff}$  is effective optical mode area in the fiber.  $\Gamma_B$  is full width at half maximum (FWHM) level of the Brillouin spectrum,  $\Omega_B$  is a frequency shift from the laser signal and  $g_p$  is Brillouin gain value at the maximum. To calculate the  $g_p$  we would need to know the parameters of the fiber:

$$g_p \equiv g_B(\Omega_B) = \frac{2\pi^2 n^7 p_{12}^2}{c\lambda_p^2 \rho_0 v_A \Gamma_B}$$
(3)

where  $\rho_0$  is density of the fiber,  $p_{12}$  is elasto-optic coefficient and *c* is a speed of light. Fig. 1 shows typical Brillouin spectra for different fibers [4]. Typical g<sub>p</sub> value for silica single mode fiber (SMF) at 1.55µm is ~5 \cdot 10<sup>-11</sup> m/W.



Fig. 1. Brillouin-gain spectra of three fibers at  $\lambda_p = 1.525 \ \mu\text{m}$ : (a) silica-core fiber, (b) depressed cladding fiber and (c) dispersion-shifted fiber. Figure is taken from ref. 4.

From the above formulas we see that we can influence the Brillouin gain spectrum by modifying the fiber in different ways. Let first discuss the parameter  $g_p$  and how we can decrease its value. Using fiber with lower refractive index *n* would significantly decrease  $g_p$  and lower SBS threshold, since it has  $P_{cr} \sim n^{-7}$ dependence. Although, most fiber lasers use silica fibers which has already one of the lowest refractive indexes of the glasses (~1.46). Changing other parameters will also have very little effect on  $g_p$  because we are quite limited by the materials we can use.

One of the effective ways to decrease the threshold of SBS is to use large mode area (LMA) fiber, which has the diameter of the mode in the optical fiber of up to  $30\mu m$  [3]. This kind of fiber will have 10 times the  $A_{eff}$  compared to the regular single mode fiber. Therefore, the SBS threshold will decrease by a factor of 10 (eq. 1). Fibers with even bigger core diameter suffer from leakage of the light from the fiber core and it is hard to make to operate in a single mode regime.

To further decrease the SBS gain we can broaden the linewidth of the seed laser [2-3]. This will lower the coherence length, thus, it is not an option for many applications. Instead, we will discuss how SBS gain will change if we change the temperature [5-6] or apply strain [1,7] to the fiber. Both effects change  $\Omega_B$ : the temperature coefficient of Brillouin shift is 1.3MHz/°K and the strain coefficient is 740MHz/% for silica fibers. For example, if we apply strain of 0.1% to the half of the length of fiber and another half is unchanged, effectively we will have 2 fibers with Brillouin gain spectra separated by 74MHz. This will decrease the SBS threshold by a factor of 2.

Typically silica fiber has a proof test of 200kpsi=1.4GPa. The Young's modulus for fused silica is 72GPa. Therefore, the maximal strain that fiber can have is 1.4GPa/72GPa~2%. For the strain of 2% we would need to apply force of  $P \cdot A = 1.4GPa \cdot \pi \cdot (62.5 \cdot 10^{-6}m)^2 = 17.2N$ . To shift the Brillouin gain peak by one  $\Delta v_B$  we would need to apply 0.068% of strain to the fiber, where  $\Delta v_B = \Gamma_B/(2\pi) = 50$ MHz is FWHM of the Brillouin spectra. Maximal factor of SBS suppression can be achieved by applying different strain to different segments of fiber is basically equal to the number of these segments 2%/0.068%=30.

L. Zhang et al. [6] demonstrated a 170W CW laser at 1064nm with the SBS threshold suppression by a factor of 7. To suppress the SBS gain different strain was applied to different segments of fiber (fig.2). Zhang used segments with equal length but the power in the fiber amplifier grows along the fiber length. Based on eq. (1) to maximize the SBS suppression we need parameter  $\int_{L_i}^{L_{i+1}} P(z) dz$  to be constant, where  $(L_{i+1}-L_i)$  is a length of the segment i. Each next segment of fiber in that case will have a shorter length due to the increase of power in the fiber amplifier.



Fig. 2. (a) Calculated signal power evolution and designed strain distribution along the fiber. (b) Calculated SBS light spectrum under the strain distribution. Figure is taken from ref. 7.

In another work by L. Zhang et al. [1] a 44W CW fiber laser at 1178nm and linewidth of 1MHz was demonstrated. In that work authors were able to get SBS suppression by a factor of 20 by applying different strain to 30 segments of fiber with different length (fig. 3).



Fig. 3. (Color online) Calculated signal power evolution (dotted), the designed strain distribution (solid, green), and the applied strain distribution (solid, blue) along the fiber. Figure is taken from ref. 1.

Applying strain to the fiber has a big advantage: it does not require any active system for control. The strain can be applied by the external force or weight. After that the fiber is fixed to a surface by epoxy. When applying epoxy we also have to consider shrinkage of the epoxy and maximum Shear stress it can hold. Shrinkage of the epoxy during the curing process can change the strain in the fiber, thus it is best to apply small amount of it. On the other hand, we have to be sure that epoxy will hold the stress from the fiber. For that reason we need to know maximum Shear stress the epoxy can hold to calculate the length of the fiber that has to have epoxy applied to:

$$2\pi \cdot r \cdot L \cdot Safety \ Factor \cdot Force = \sigma_{max} \tag{4}$$

Another method to suppress the SBS in fiber lasers is to change the temperature of the fiber (fig. 4). Jeong et al. [6] demonstrated a 500W CW laser at 1064nm with the linewidth below 60kHz. The expected SBS threshold is at 110W for that system, but even at 500W SBS was not observed due to the passive gradient of the temperature along the fiber length. The passive temperature gradient in the fiber lowered the SBS gain by more than a factor of 5 in that case. The temperature difference between amplifier fiber ends estimated to be 190°K. For such temperature difference the Brillouin shift would equal to 190°K\*1.3MHz/°K=247MHz. Maximal reduction of SBS gain in that case can be ~6 if the temperature curve follows the power curve, which should be quite close in a counter propagating amplification scheme.



Fig. 4. Plot Brillouin gain spectrum at six different temperatures. Figure is taken from ref. 5.

This kind of passive gradient is very beneficial for the CW laser with the counter propagating scheme, when pump light is injected into the output of the amplifier. In that case the pump power and the signal power are the highest at the output. Therefore the output end of the fiber has much higher temperature compared with the input end. Such passive gradient will not be efficient in the co propagating amplification scheme.

Passive temperature gradient is not going to work for lasers where average power is less than 10W, since for such small powers the temperature does not raise significantly. For example, 10W average power laser with a repetition rate of 10kHz and pulse duration of 100ns will have the peak power of 10kW. At such

high peak power most of the light will be reflected back due to SBS in a 1 meter of single mode fiber. In that case we would need to design an active system that would create temperature gradient along the fiber.

Finally, to estimate the maximal suppression of the SBS gain in the fiber amplifier we would need to calculate the P(z) and for each segment  $L_i L_i + I(\int_{L_i}^{L_{i+1}} P(z) dz = \text{constant})$  apply strain or temperature. Strain and temperature can also be applied together to increase number of segments. In that case we also should take into account that properties of the epoxy change with temperature. The estimated maximum suppression possible by applying strain to the fiber is factor of 30, and with the temperature gradient of 200°C it is factor of 6. To realize such results one would have to know the exact distribution of power along the fiber length, which is hard to estimate without cutting down the amplifier fiber and measuring the power.

## References

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