Effects of Forced Airflow Cooling on Laser Beam Heating of Volume Bragg Gratings

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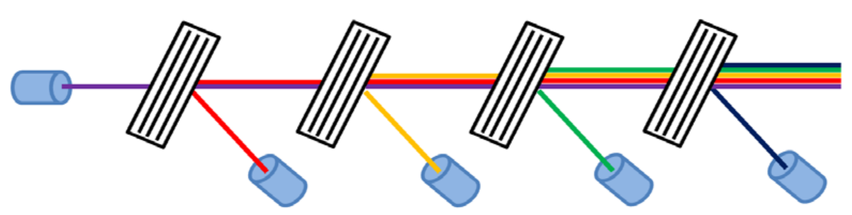
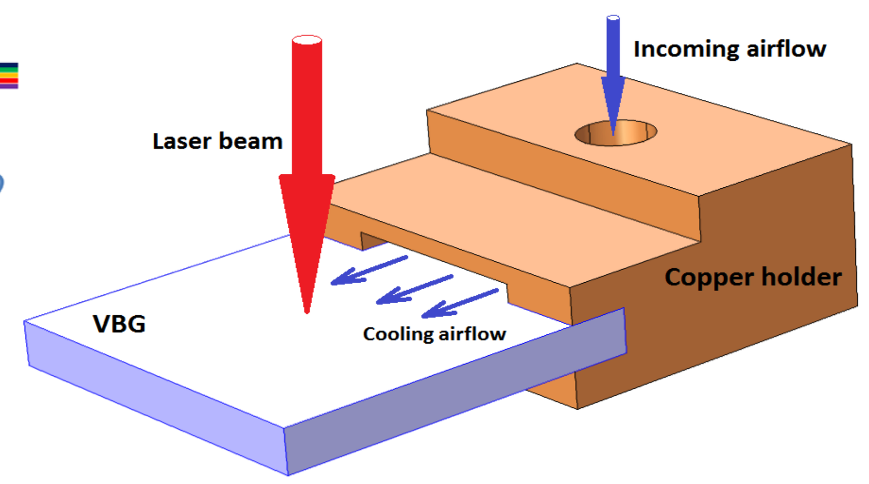
Experimental Setup

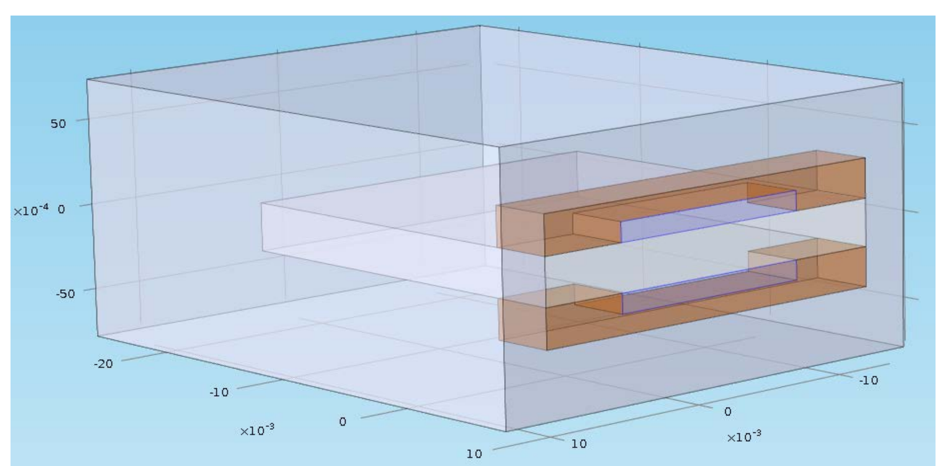
Volume Bragg Gratings (VBG) are holographic elements recorded in Photo-Thermo-Refractive (PTR) glass. They are a relatively new invention of the last decade that has been successfully used for high power and high spectral density laser beam combining.

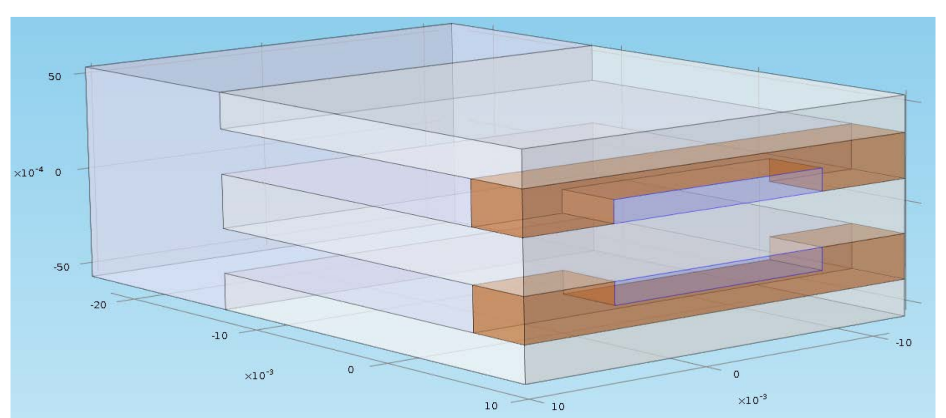




The VBG is one of the constituting elements of the laser beam combining system proposed and experimentally realized in [1]. In the system a set of four gratings is used to combine five laser beams with total output intensity of 750 W.

Geometric Model of the Cooling Setup





Part of the system beyond the end of the grating closest to the holder is not significant for the simulation results and effectively can be left out of the model to provide for simulations that are more efficient and consume less computational resources. On the left there is shown the actual COMSOL geometry used in our simulations. The airways were essentially substituted with two airflow inlets on the border adjacent to the grating, and the whole glass plate of grating together with metallic holder submerged into an air box.

The alternative case of the system the two glass plates in shape of rectangular parallelepipeds are "glued" to the top and bottom sides of the metallic holder. The system is still submerged into an air box but the top and bottom borders of this box are now adjacent to borders of the limiting glass plates

Main dimensions of system with unrestricted VBG

Grating	$2.74\cdot10^{-3}$ x $2.2\cdot10^{-2}$ x $2.2\cdot10^{-2}$	m
Metallic Holder	$2.275\cdot10^{-3}$ x $3.5\cdot10^{-3}$ x $2.2\cdot10^{-2}$	m
Air Inlet (x2)	$1.135\cdot10^{-3}$ x $1.2\cdot10^{-2}$	m
Air Box	$1.507\cdot10^{-2}$ x $2.748\cdot10^{-2}$ x $3.304\cdot10^{-2}$	m

Main dimensions of system with restricted VBG

Limiting Glass Plates	$1.85\cdot10^{-3}$ x $2.2\cdot10^{-2}$ x $2.2\cdot10^{-2}$	m
Air Box	$2.2\cdot10^{-2}$ x$3.304\cdot10^{-2}$ x $1.098\cdot10^{-2}$	m

[1] D. Drachenberg, I. Divliansky, V. Smirnov, G. Venus, and L. Glebov, "High Power Spectral Beam Combining of Fiber Lasers with Ultra High Spectral Density by Thermal Tuning of Volume Bragg Gratings." Proc. of SPIE vol. 7914 (2011).

Thermal Model

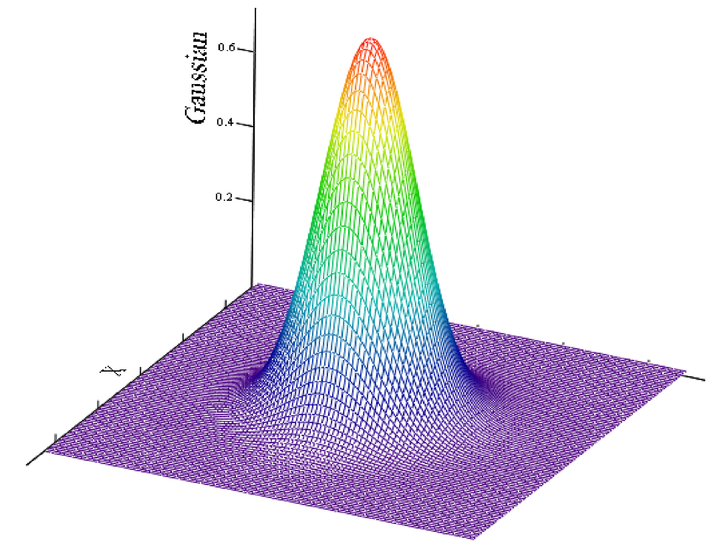
To complete the model with corresponding material characteristics we used both COMSOL materials library and created our own material to use parameters specific for PTR glass only. Air was chosen for the volume of air box, metallic holder was made out of copper, and the VBG was chosen to be made of our newly created material with parameters outlined in the Table.

Coefficient of Thermal Expansion	$9.5\cdot10^{-6}$	1/K
Heat Capacity at Constant Pressure	840	J/(kg*K)
Density	2500	kg/(m^3)
Thermal Conductivity	1.05	W/(m*K)
Young's Modulus	$6.4\cdot10^{10}$	Pa
Poisson Ratio	0.2	dimensionless
Refractive Index	1.4891	dimensionless

- To study different heat transfer mechanisms, the "Thermal Stress" interface from module "Structural Mechanics" was chosen.
- "Thermal Linear Elastic" model was chosen for domains containing VBG and copper holder.
- Boundary conditions were chosen by the "Free" model for all boundaries except the boundaries of the copper holder adjacent to the air box.
- For those adjacent boundaries a "Fixed Constraint" model was chosen.
- Heating of the VBG with laser beam was taken into account by introducing model "Heat Source" for domains of VBG and of copper holder.
- The model "Heat Transfer of Fluids" was responsible for transfer of heat from surfaces of the VBG and the holder.
- Model "Outflow" is applied to the border of the air box furthest away from the inlet of airflow
- Boundaries of the air box were set to a constant temperature by a model "Temperature".

Heating of the grating was simulated to have 2D Gaussian distribution of the following form:

$$Q_{in}(x,y,z) = P_0 \cdot \alpha \cdot \frac{1}{\pi \cdot \sigma_x \cdot \sigma_y} \cdot \exp\left(-\frac{(x-x_0)^2}{2\cdot{\sigma_x}^2} - \frac{(y-y_0)^2}{2\cdot{\sigma_y}^2}\right) \cdot \exp(-\alpha\cdot|z|)$$



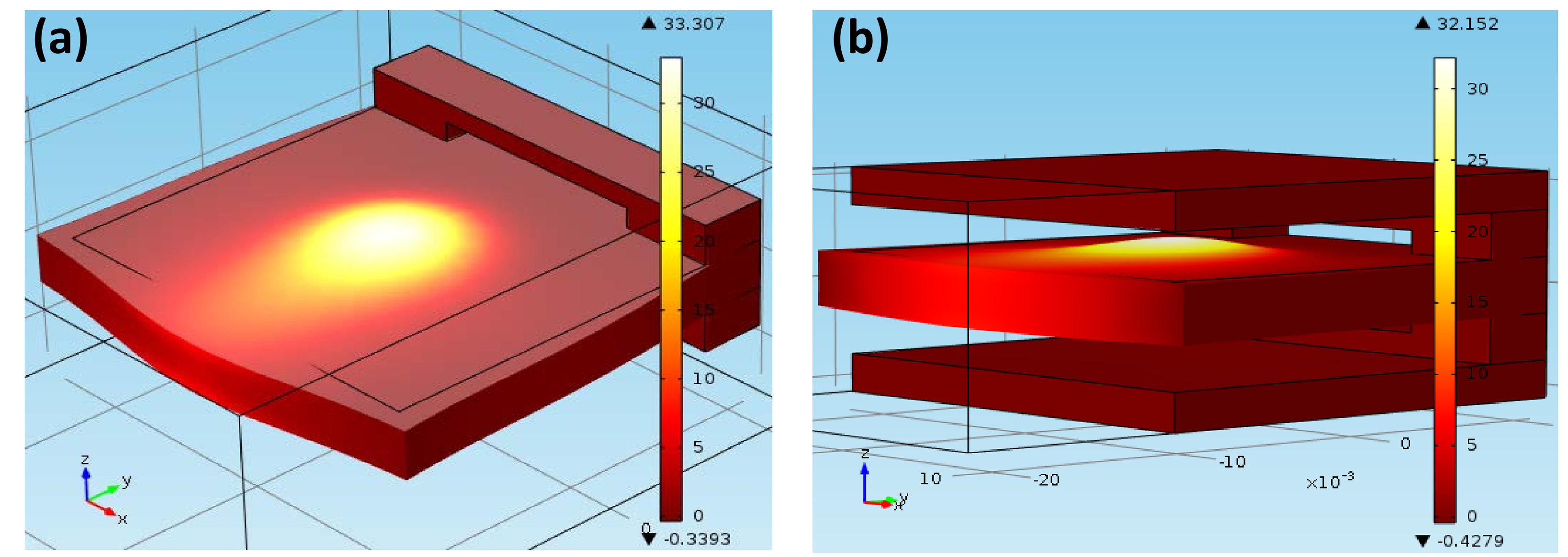
The heating beam was symmetrical with diameter of $6\cdot10^{-3}$ m (FWe^{-2}IM).

Fluid Dynamics Model

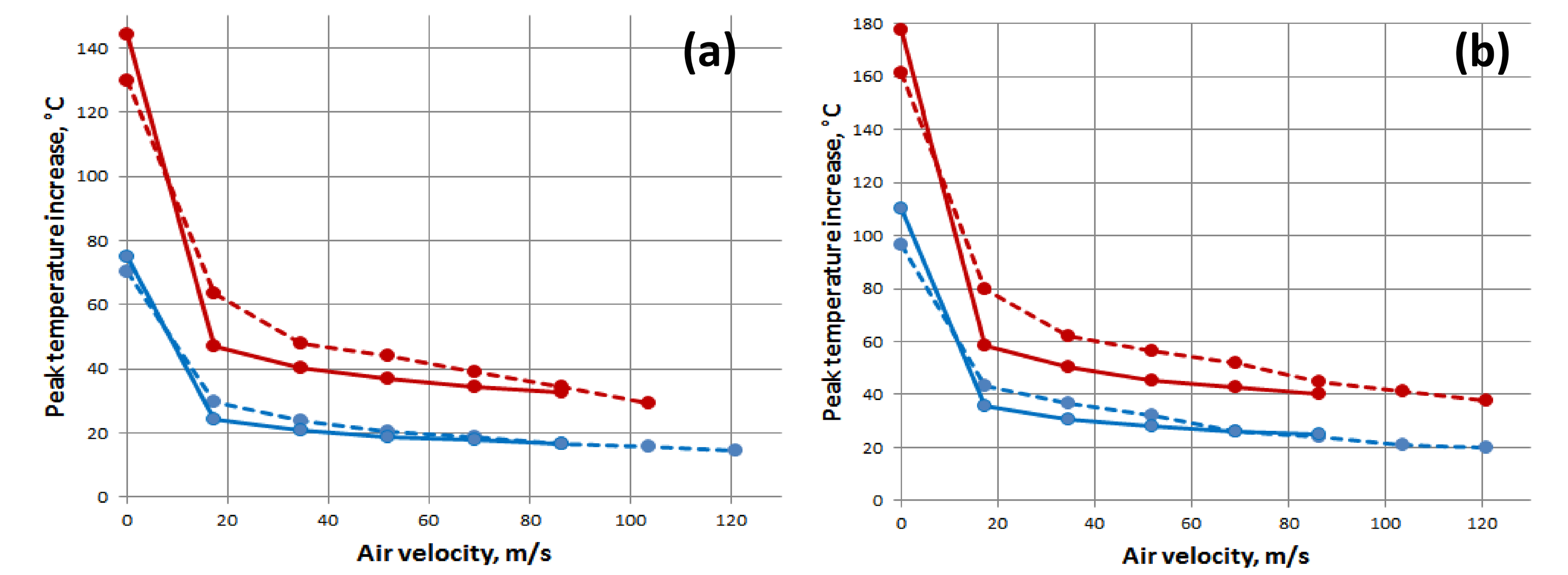
- The interface "Turbulent Flow, k-ε" from module "Fluid Flow" was used.
- Models "Fluid Properties" and "Initial Values" specified properties of air and initial velocities, correspondingly.
- The default model "Wall" applied to all surfaces submerged into the air box.
- An air influx and control of its initial velocity is performed within a model "Inlet". This model was applied to the surface area in the place where air shafts meet the border of the air box.
- Influx velocity vector was set in perpendicular to the plane of the inlets, which in turn, is parallel to the main plain of the VBG.
- The excess of air created by this additional influx is taken away from the simulated system by application of a model "Outlet" to the border located farthest away from the VBG.
- A "Symmetry" model is implemented to all the remaining borders of the air box.

Comparison of Experimental and Simulation Results

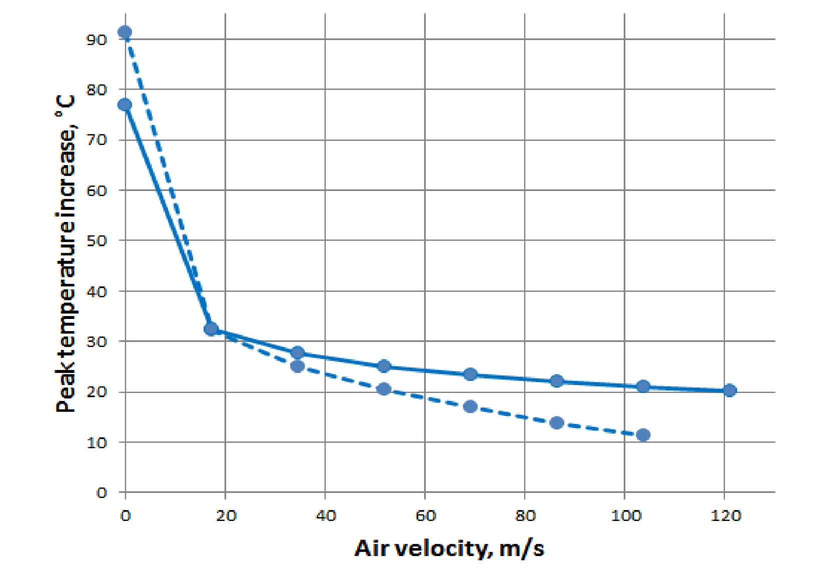
For a case of unlimited VBG we modeled four laser beam power values of 4.5kW, 6.7kW, 8.9kW and 11kW. In case of VBG restricted by glass plates the power values of 4.5kW, 6.1kW, 6.7kW, 8.9kW and 11kW were chosen. For each of the laser beam power we conducted simulations with the following cooling airflows (in m/s): 0.0, 17.3, 34.6, 51.9, 69.1, 86.4, 103.7, 121.



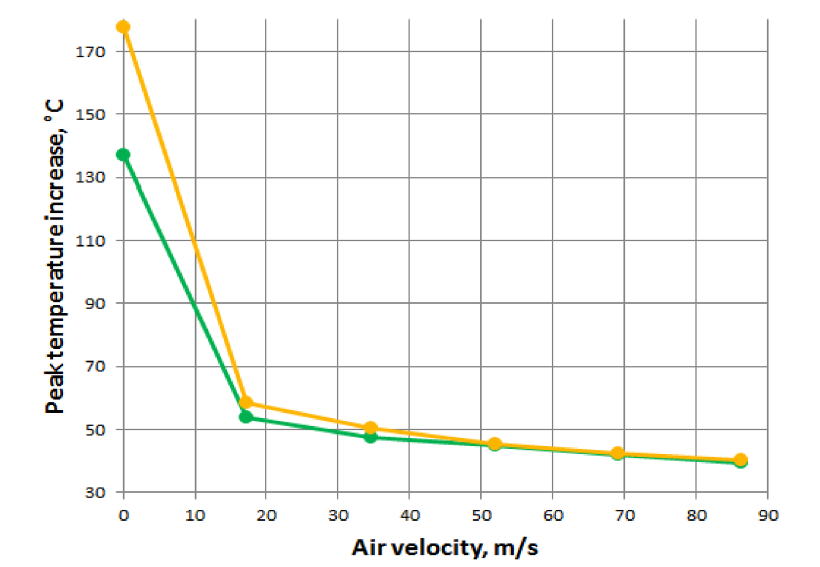
An example of distribution of surface temperature increases and corresponding thermal deformations of VBG for laser power of 11kW and airflow of 86.4 m/s (a) for unrestricted VBG and (b) for restricted VBG.



Peak temperature increase compared to the ambient temperature of the system for unrestricted VBG. In all cases, solid and dashed lines are for simulated and experimental data, respectively. (a) Blue curves correspond to laser power of 4.5kW and red curves correspond to laser power of 8.9kW; (b) Blue curves correspond to laser power of 6.7kW and red curves correspond to laser power of 11kW.



Peak temperature increase compared to the ambient temperature of the system for restricted VBG at laser power of 6.1kW. Solid and dashed lines are for simulated and experimental data, respectively.



Simulation results on peak temperature increase (compared to the ambient temperature) for laser power of 11kW. Yellow curve corresponds to unrestricted VBG and green curve to a VBG limited by glass plates.

Conclusions

Thus we have shown via COMSOL modeling and physical experiment that forced air cooling of VBG is an inexpensive and efficient way of substantially reducing negative effects of thermal deformation of PTR glass and this effect is being enhanced in case of limiting a VBG by a pair of glass plates.