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Glass City Center - Toledo, OH
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Ultrafast Laser Welding Of Soda Lime Silicate Glasses - Modeling And Experimental Results*

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SUNY Distinguished Professor of Research

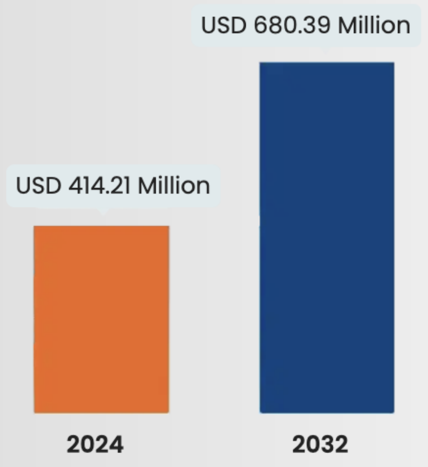
* Based on graduate works of Dr. Sean Locker (now with Corning Inc.) and Kathleen Matthies at Alfred University

Vacuum Insulated Glass (VIG) Market

Global Vacuum Insulated Glass Market

Market Size in USD Billion

CAGR : 6.40%



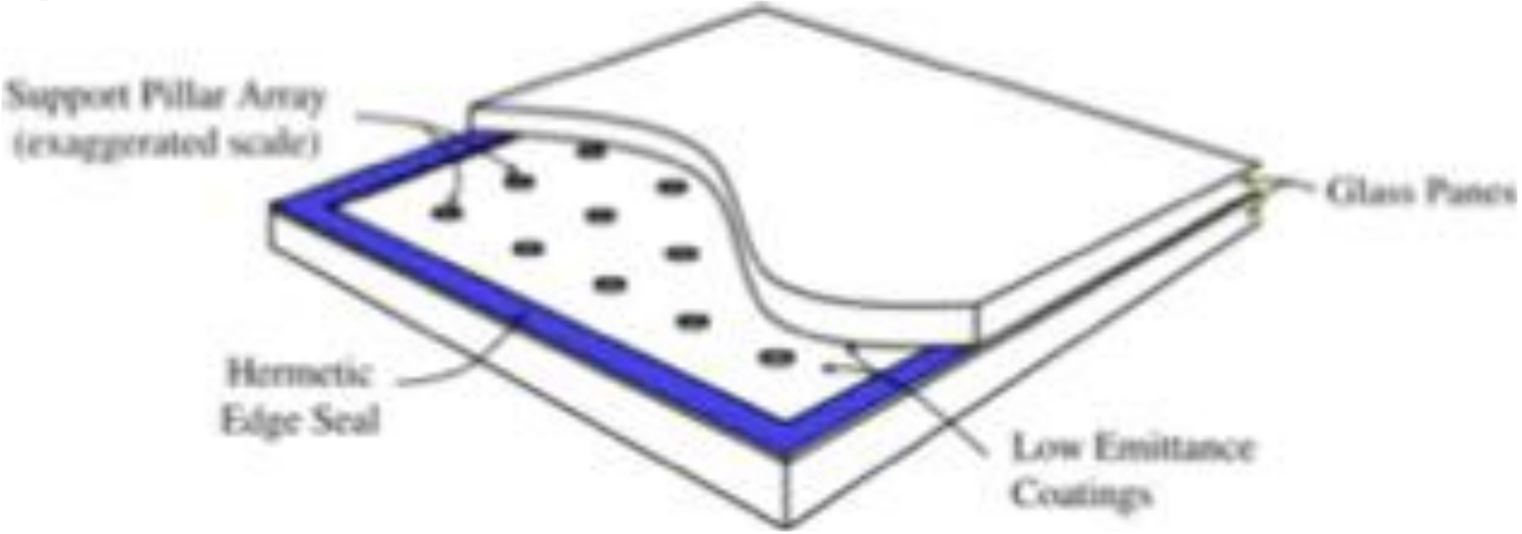
Forecast Period	2025 –2032
Market Size (Base Year)	USD 414.21 Million
Market Size (Forecast Year)	USD 680.39 Million
CAGR	6.40 %
Major Markets Players	• AGC Inc • Panasonic Corporation • LandGlass Technologies Co. Ltd • Nippon Sheet Glass Co Ltd • and Guardian Glass

Global Vacuum Insulated Glass Market Segmentation, By Product (Dual Glaze Vacuum Insulated Glass and Triple Glaze Vacuum Insulated Glass), Application (Roof Lights, Windows, Doors, Roof Glazing, Glass Façade, and Others), End-Use (Residential, Commercial, and Industrial) - Industry Trends and Forecast to 2032

Source: Global Vacuum Insulated Glass Market Size, Share, and Trends Analysis Report – Industry Overview and Forecast to 2032; https://www.databridgemarketresearch.com/reports/global-vacuum-insulated-glass-market

Vacuum Insulation Glazing (VIG) Process

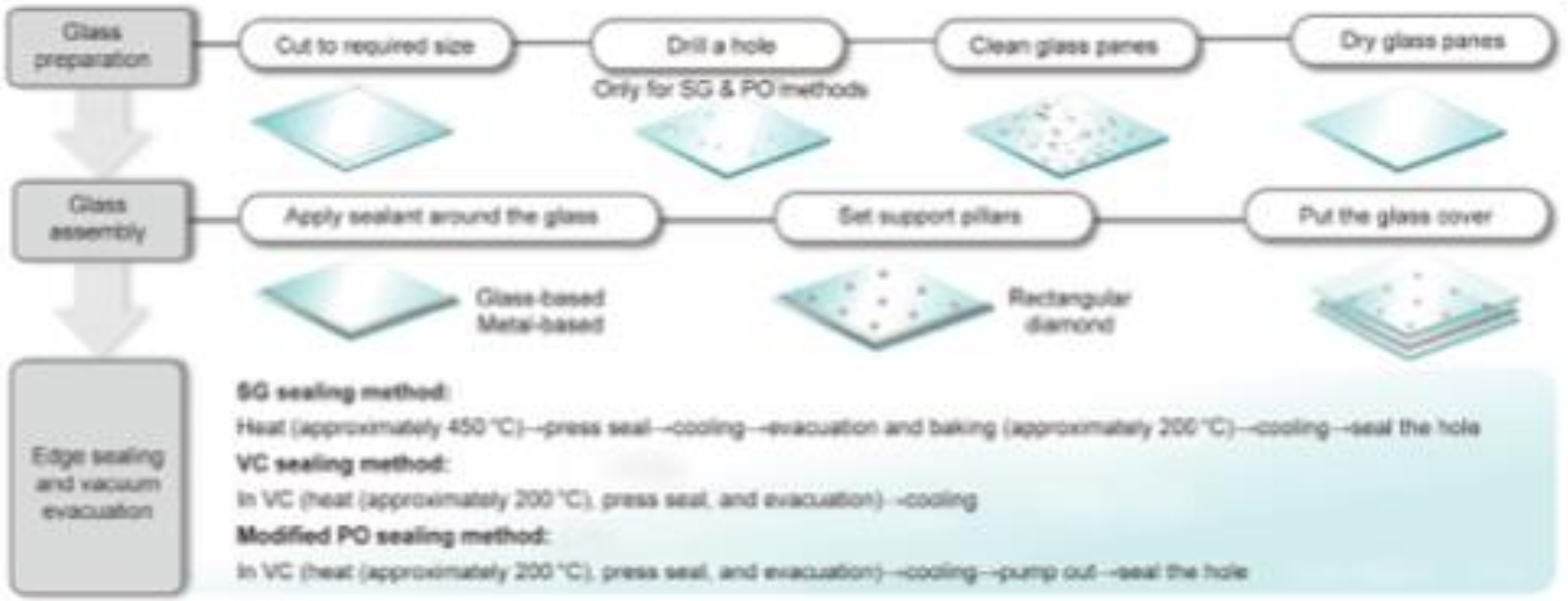
- Cutting-edge technology - reduce heat transfer through windows - **energy savings**.
- Promising - thermal transmittance levels around 0.5W/m²·K (compared to traditional double-glazed or gas-filled insulating glass units (IGUs)) – **carbon neutrality in buildings**.



Source:: W. Jung, D. Kim, and S. H. ko, "Recent Progress in High-Efficiency Transparent Vacuum Insulation Technologies for Carbon Neutrality," *Inter. J. of Precision Engineering and Manufacturing-Green Technology* **11**, 1681–1702 (2024); doi.org/10.1007/s40684-024-00623-x

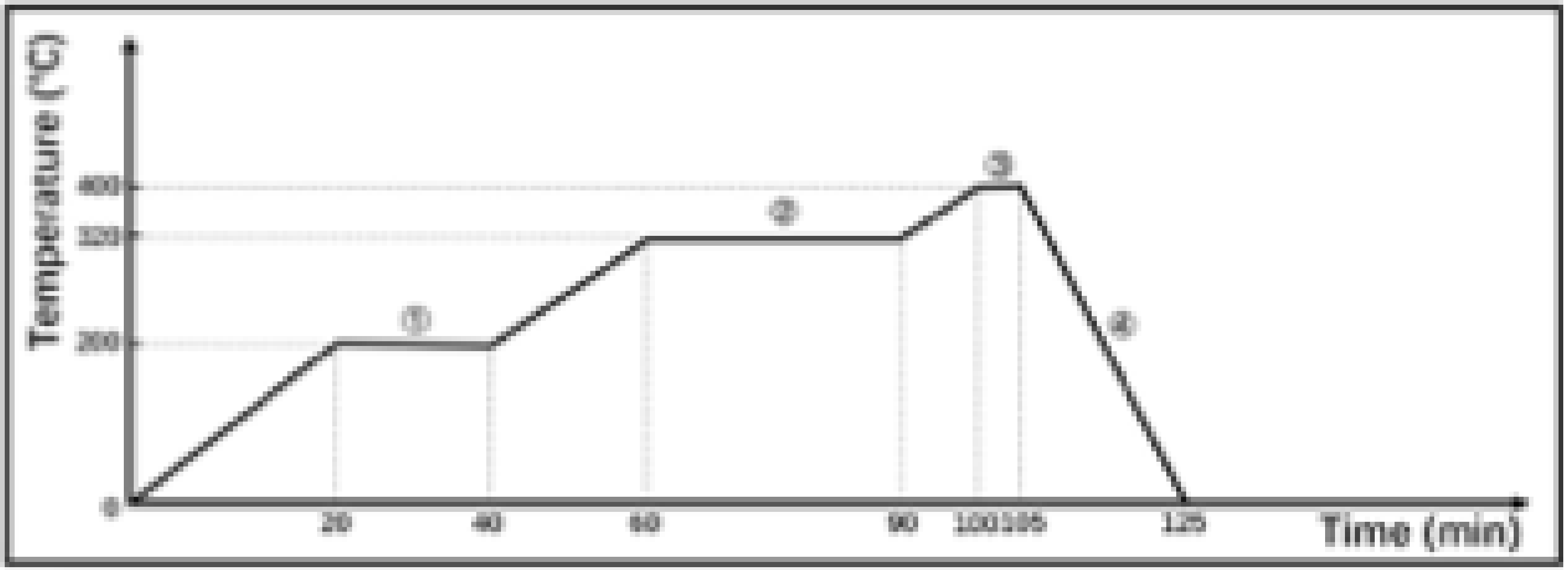
Vacuum Insulated Glazing (VIG) Process

Detailed Steps of Three Vacuum Glazing Fabrication Methods



Source:: J. Peng, Y. Tan, Y. Fang et al., “Excellent Insulation Vacuum Glazing for Low-Carbon Buildings: Fabrication, Modeling, and Evaluation,” *Engineering*, https://doi.org/10.1016/j.eng.2024.11.027

Vacuum Insulation Glazing (VIG) Process



Heating	① Dry	② Pre-bake	③ Working	④ Cooling
10°C/min	200°C, 20min	320°C, 30min	400°C, 5min	20°C/min

Source:: W. Jung, D. Kim, and S. H. ko, "Recent Progress in High-Efficiency Transparent Vacuum Insulation Technologies for Carbon Neutrality," *Inter. J. of Precision Engineering and Manufacturing-Green Technology* **11**, 1681–1702 (2024); doi.org/10.1007/s40684-024-00623-x

Vacuum Insulation Glazing (VIG) Process

- **Challenges:**
  - Significantly **higher cost** than standard IGUs and triple-glazed windows meeting passive house standards - **lengthy evacuation times and high processing temperatures**
- **Cost reduction:**
  - **Optimizing** manufacturing processes
  - **Low-melting-point** solders for hermetic sealing
  - **Localized heating** techniques to shorten production times.

Ultrafast laser pulses!

Source:: W. Jung, D. Kim, and S. H. ko, "Recent Progress in High-Efficiency Transparent Vacuum Insulation Technologies for Carbon Neutrality," *Inter. J. of Precision Engineering and Manufacturing-Green Technology* **11**, 1681–1702 (2024); doi.org/10.1007/s40684-024-00623-x

Recent Publications and Presentations

Publications

- S. Locker, S. Goyal, M. E. McKenzie, S. K. Sundaram, and C. Ungaro, "Laser-Induced Structural Modification in Calcium Aluminosilicate Glasses Using Molecular Dynamic Simulations," *Scientific Reports*, 11:9519 (2021). DOI: 10.1038/s41598-021-88686-7
- **S. Locker, J. A. Clark, and S. K. Sundaram, "Structural Modifications of Soda-Lime Silicate Glasses Using Femtosecond Pulse-Laser Irradiation,"** ***Intern. J Appl. Glass. Sci.*****, 12 July 2020; DOI: 10.1111/ijag.15823**
- **S. Locker and S. K. Sundaram, "Ultrafast Modification of Oxide Glass Surface Hardness,"** ***Appl. Phys. B, 125: 225 (2019). https://doi.org/10.1007/s00340-019-7334-5***

Presentations

- **K. Matthies and S. K. Sundaram,** ***"Ultrafast Laser Welding and Characterization of Glasses and Welded Joints," 16th Pacific Rim Conference on Ceramic and Glass Technology and The Glass & Optical Materials Division Meeting (GOMD 2025), May 4–9, 2025, Vancouver, BC, Canada***
- **S. K. Sundaram, "Ultrafast Glass Engineering," 82nd Glass Problems Conference, 2021.**
- S. K. Sundaram, "Ultrafast Glass Science – Fundamentals and Applications," (Invited talk), Materials Science and Technology MS&T 2019, Oregon Convention Center, Portland, OR September 29-Octpber 3, 2019.
- S. K. Sundaram, "Ultrafast Glass Science and Engineering (Short Course)," 25th International Congress on Glass (ICG 2019), American Ceramic Society, Glass & Optical Materials Division (GOMD) 100 years, Boston, MA, June 9-14, 2019.
- S. K. Sundaram, "Accelerating Strengthening in Silicate Glasses (Invited)," 25th International Congress on Glass (ICG 2019), American Ceramic Society, Glass & Optical Materials Division (GOMD) 100 years, Boston, MA, June 9-14, 2019; Also participated in Flat Glass Innovation Roundtable.

Modeling vs. Experimental Results

S. Locker and S. K. Sundaram, "Ultrafast Modification of Oxide Glass Surface Hardness," Appl. Phys. B, 125: 225 (2019). https://doi.org/10.1007/s00340-019-7334-5

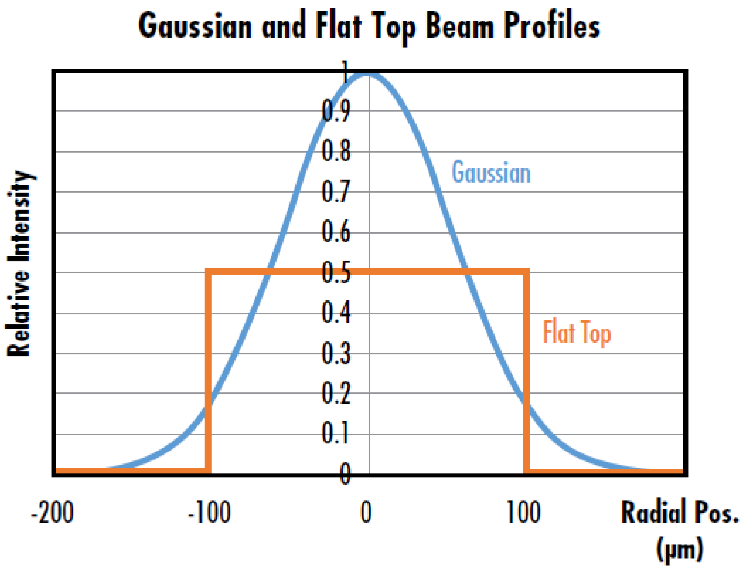
S. Locker, J. A. Clark, and S. K. Sundaram, "Structural Modifications of Soda-Lime Silicate Glasses Using Femtosecond Pulse-Laser Irradiation," *Intern. J Appl. Glass. Sci.*, 12 July 2020; DOI: 10.1111/ijag.15823

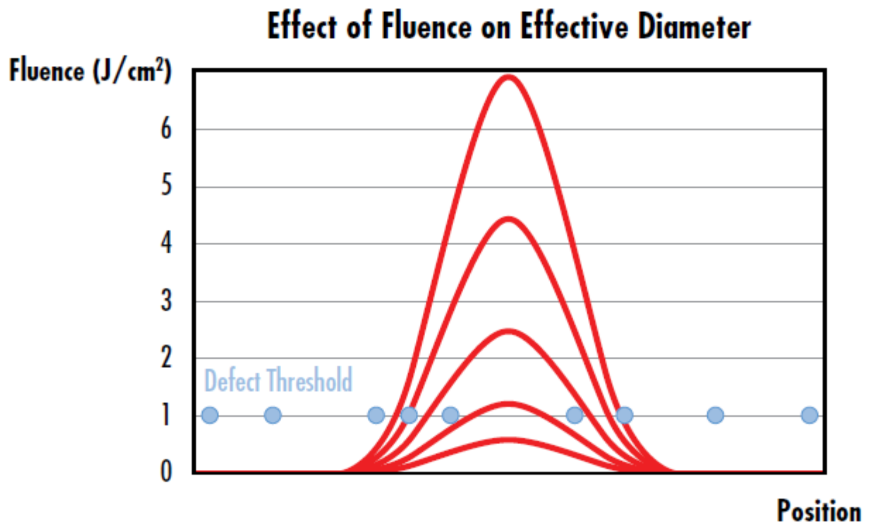
Ultrafast Laser Parameters

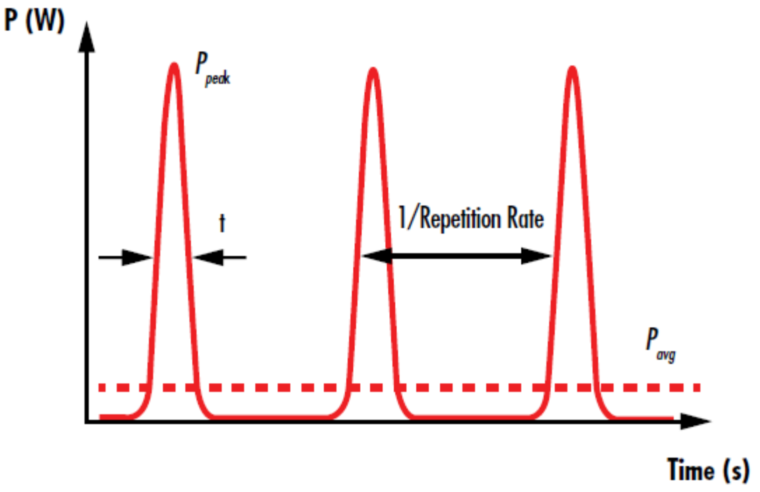
Irradiance or Power Density = Power/Area

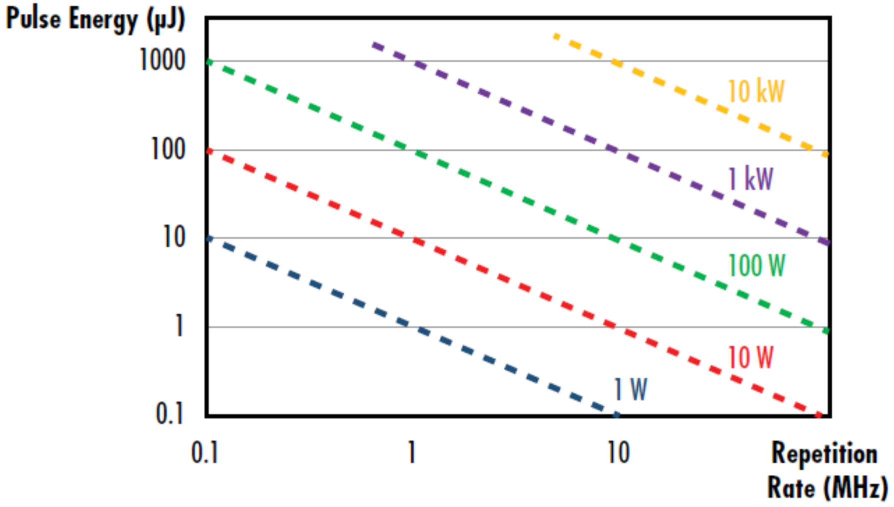
Pulse Energy
= Average Power/Repetition Rate (# of pulses/s)

Fluence or Energy Density
= Pulse Energy/Area



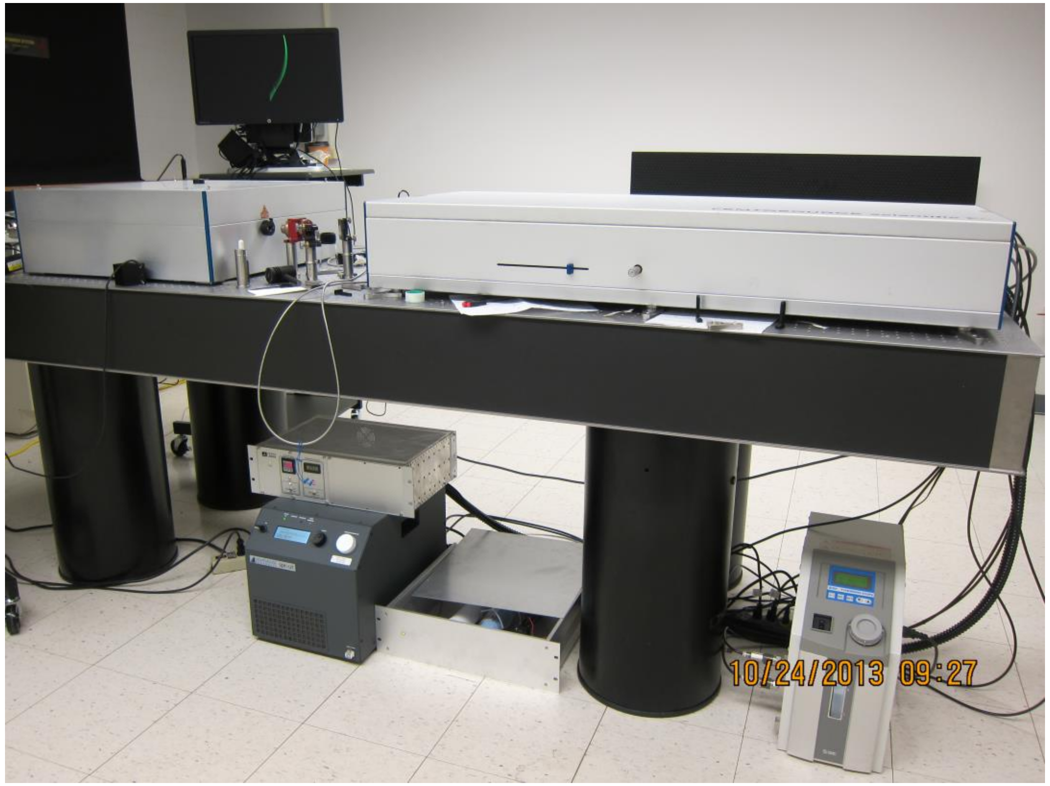




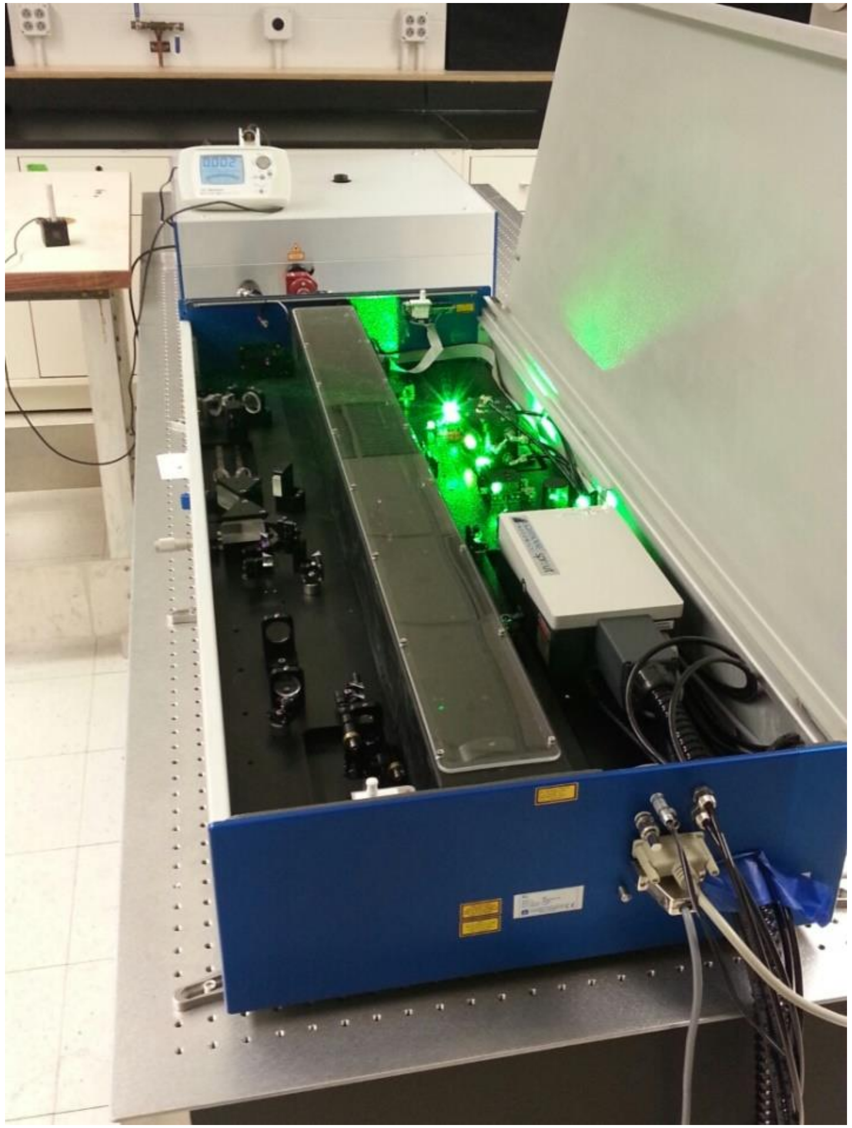


Source: https://www.edmundoptics.com/resources/application-notes/lasers/understanding-and-specifying-lidt-of-laser-components/

Femtosecond Laser System at AU



FEMTOLASER Scientific XL 500 - Average power: 2.5 W, Repetition rate: 5.1 MHz, Pulse duration: **< 50 fs**, Pulse energy: **500 nJ**, Peak power: >10 MW, Wavelength: 800 nm; Beam diameter: < 5 mm; Beam divergence: < 2 mrad



Ultrafast Laser Modification of Glasses

- A FEMTOLASER Scientific XL 500 pulse laser using **a wavelength of 800 nm, pulse energy of 500 nJ and duration of less than 50 fs** was used to treat the surface of various silicate glasses.
- Surface hardness of these glasses increased by about **13-14% with no significant change in surface chemistry or induced residual stress layers**. Densification of glass on laser irradiation is likely the causing of this increase in surface hardness.

Source: S. Locker and S. K. Sundaram, "Ultrafast Modification of Oxide Glass Surface Hardness," *Appl. Phys. B*, **125**: 225 (2019). https://doi.org/10.1007/s00340-019-7334-5

Ultrafast Laser Modification of Glasses

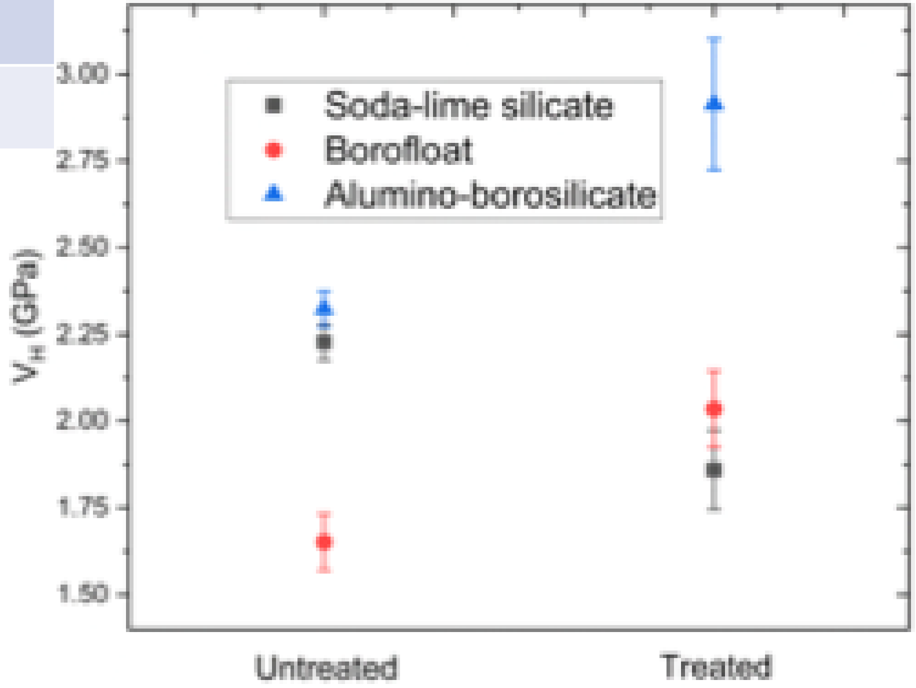
XPS elemental surface concentration

	B	O	Na	Mg	Al	Si	K	Ca	Sn
SLS untreated	-	66.4	2.5	1.7	0.7	24.6	1.1	1.8	1.3
SLS treated	-	66.3	3.0	0.9	0.5	25.3	1.2	1.6	1.2
ABS untreated	2.8	65.5	1.5	1.3	1.0	25.8	1.3	0.2	0.6
ABS treated	2.4	67.1	1.1	0.2	0.8	26.2	1.1	0.4	0.6
Borofloat untreated	3.0	66.1	0.7	0.1	0.8	28.9	0.4	-	0.0
Borofloat treated	2.7	67.5	0.6	-	0.7	28.0	0.3	-	0.1

- The **ABS** glass surface has undergone **a densification of 5.2%** after laser exposure while the **SLS** surface density was **reduced by 5.7%**.
- Mechanisms:
  - Reducing the bonding distance and angle on Si–O sites results in **densification**
  - Increasing them causes **decompaction** and decrease in density.

X-ray reflectometry

Composition	Surface	Roughness (nm)	Profile	Density (g/cm^3)
ABS	Untreated	1.1946	No gradient	2.20
ABS	Treated	0.8288	No gradient	2.32
SLS	Untreated	1.314	No gradient	2.65
SLS	Treated	1.505	No gradient	2.50



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Ultrafast Laser Modification of Glasses

- Femtosecond pulse laser radiation (**250 fs, 1030 nm**) of alkali and alkaline earth modified **soda-lime silicate (SLS) glasses** underwent a **densification process dependent on pulse energy and glass-network connectivity confirmed by Raman spectroscopy**.
- Sodium modification leads to **larger shift in the laser modified Q^3 band position and width** compared to the calcium modification.
- Increasing laser fluence affects the **position of Q^3 Si-O stretching mode** as well as the band width, indicating the increased degree of disorder laser pulses induce.

Source: S. Locker, J. A. Clark, and S. K. Sundaram, "Structural Modifications of Soda-Lime Silicate Glasses Using Femtosecond Pulse-Laser Irradiation," *Intern. J Appl. Glass. Sci.*, 12 July 2020; DOI: 10.1111/ijag.15823

Ultrafast Laser Modification of Glasses

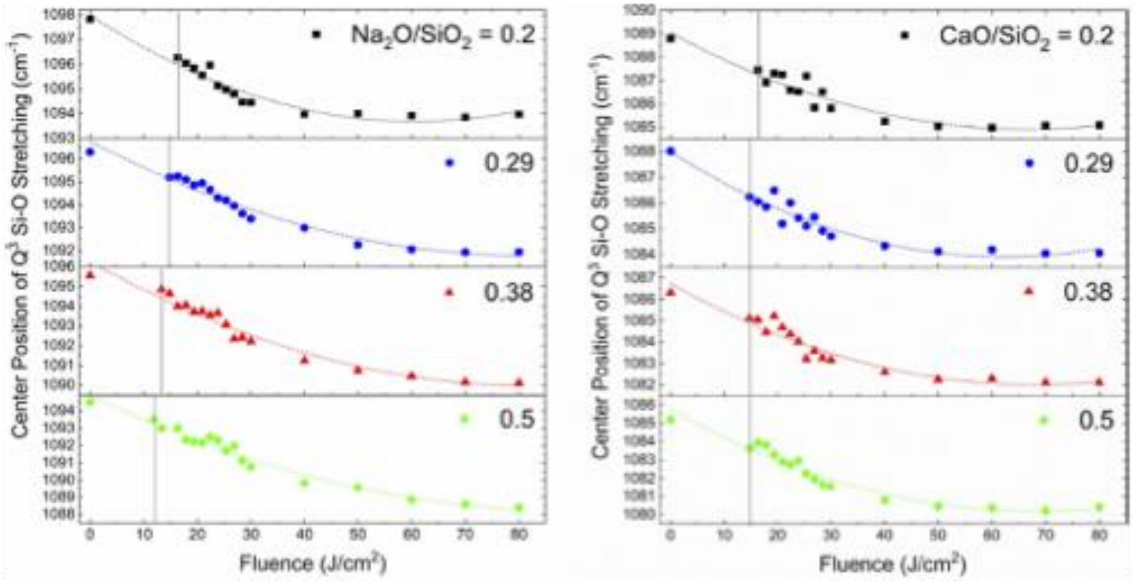


FIGURE 4 Deconvolution of Raman spectroscopy high-frequency region Q^3 Si-O stretching band position as a function of laser fluence, (left) Na_2O/SiO_2 concentration and (right) CaO/SiO_2 concentration. The dash line is a best fit quadratic intended as a visual guide. Grey vertical lines indicate the crater-ablation threshold at the given experimental laser conditions

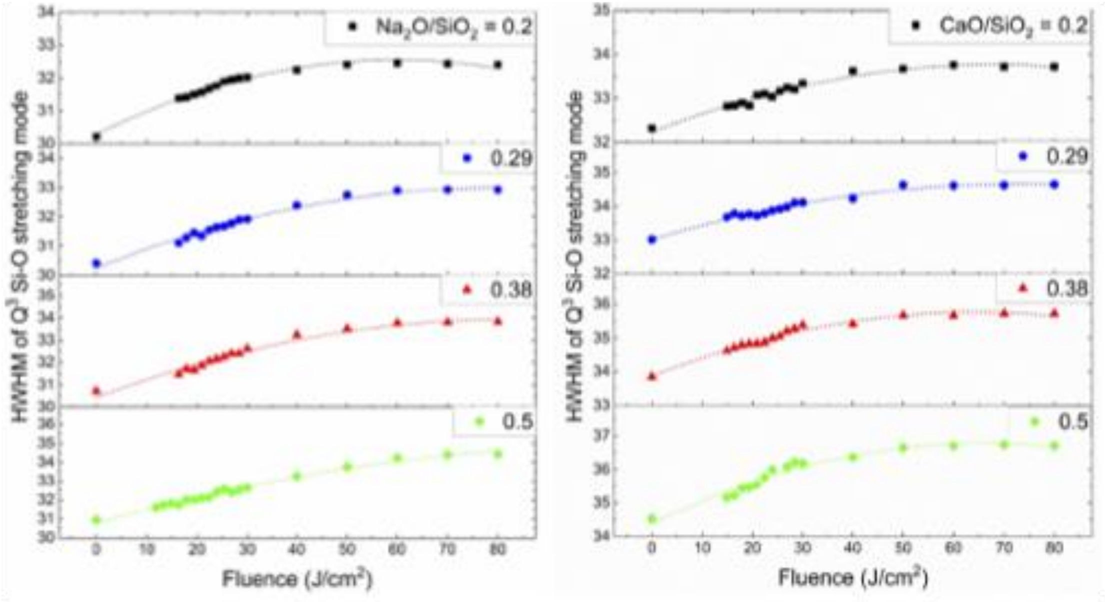


FIGURE 5 HWHM of Raman $Q^{3'}$ and Q^3 Si-O stretching of femtosecond-laser modified SLS glasses. Reference value for the pristine material is given at 0 J/cm^2

Source: S. Locker, J. A. Clark, and S. K. Sundaram, "Structural Modifications of Soda-Lime Silicate Glasses Using Femtosecond Pulse-Laser Irradiation," *Intern. J Appl. Glass. Sci.*, 12 July 2020; DOI: 10.1111/ijag.15823

Laser Welding of Soda-Lime Silicate Glass

K. Matthies and S. K. Sundaram, “Ultrafast Laser Welding and Characterization of Glasses and Welded Joints,” 16th Pacific Rim Conference on Ceramic and Glass Technology and The Glass & Optical Materials Division Meeting (GOMD 2025), May 4–9, 2025, Vancouver, BC, Canada

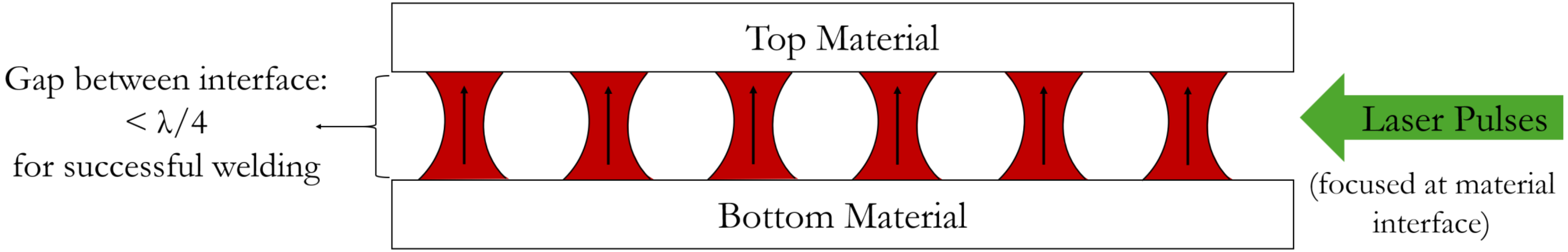
S. K. Sundaram, “Ultrafast Glass Engineering,” 82nd Glass Problems Conference, 2021.

Laser Welding of Glasses

- Ultrafast laser pulses can **modify local glass structure** (bond and network changes) significantly, therefore changing glass properties.

- Glass at interface simultaneously melted and quenched to form bonded area – via localized focus of laser pulse energy - utilizing **multiphoton nonlinear absorption at high repetition rates** to deposit enough energy to melt glass at the interface.

Laser Welding of Glasses



Glass Composition	
	Mol %
SiO_2	72.80%
Al_2O_3	0.20%
Fe_2O_3	0.090%
CaO	8.75%
MgO	3.80%
Na_2O	13.65%
K_2O	0.15%
SO_3	0.25%
TiO_2	0.01%

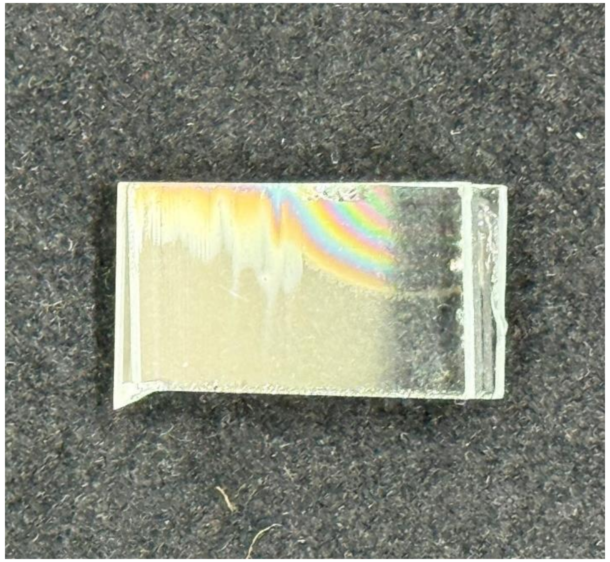
Welding and Filamentation

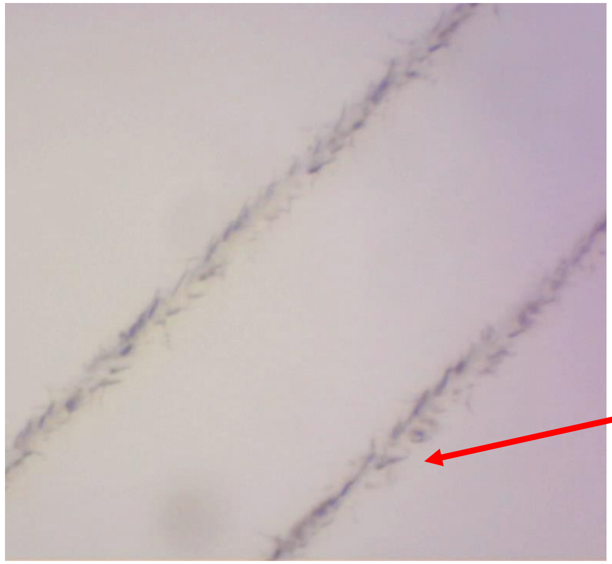
- Welded between **2 pieces of 1” x 1” commercial SLS** glass using **HyperRapid NXT** ultrafast laser to create weld lines
- Setup and experiment completed by Coherent Inc.

Laser Processing Parameters

Parameters	Filamentation	Welding
Wavelength (nm)	1064	1064
Pulse Duration (ps)	15	15
Repetition Rate (kHz)	1000	155
Burst Count	1	4
HRNXT Transmission (%)	22	55
Filamentation Spacing (µm)	6.0	6.0
Filamentation Speed (mm/s)	2	50

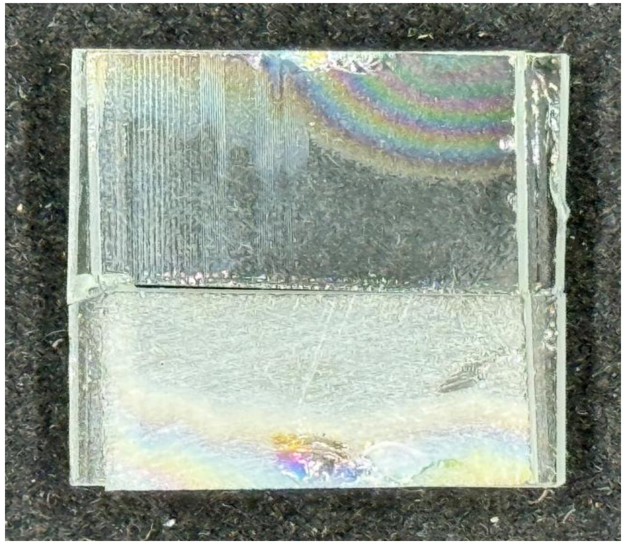
Laser Welded Glasses





	Sample Designation		
	Single	**Double**	**Welded 1**
Weld Pattern	N/A	N/A	Single Direction

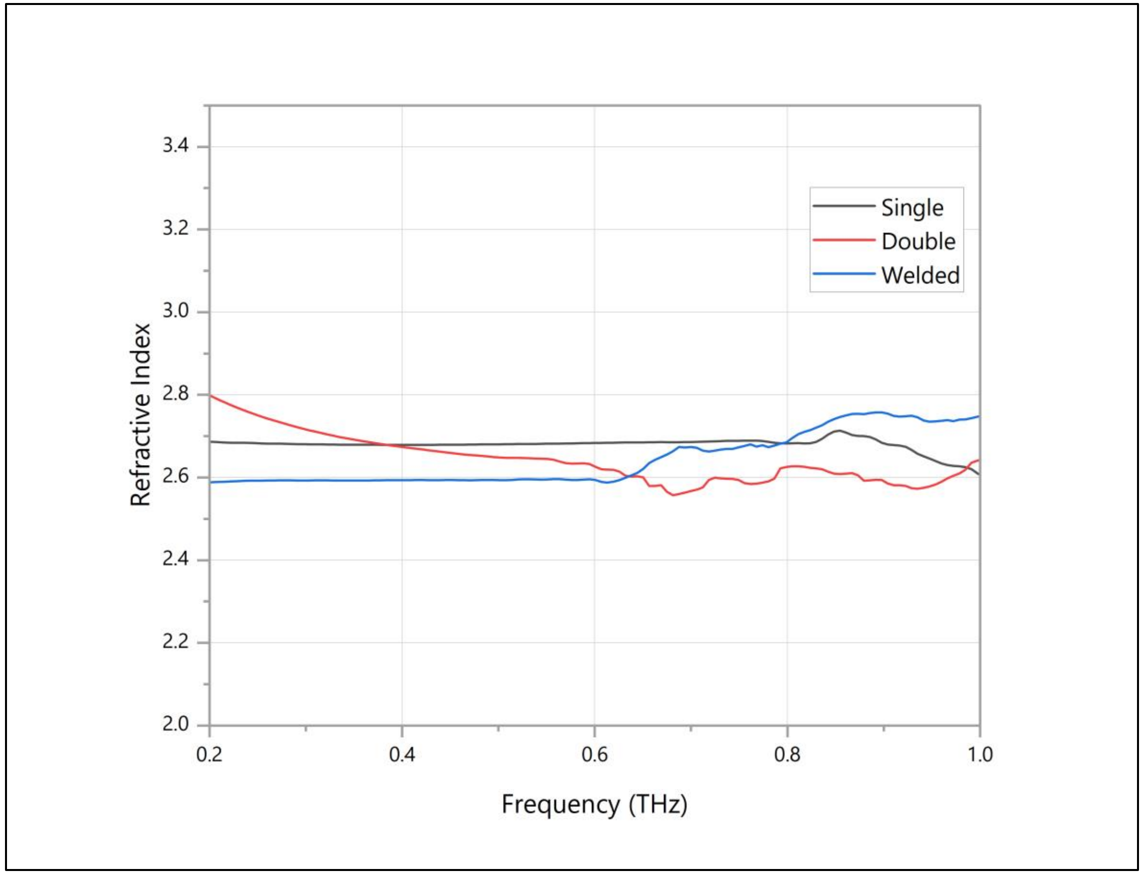
- Microscopic images of welds were taken at 14x magnification.
- Welded sample cut in half and ground down close to the interface for characterization.

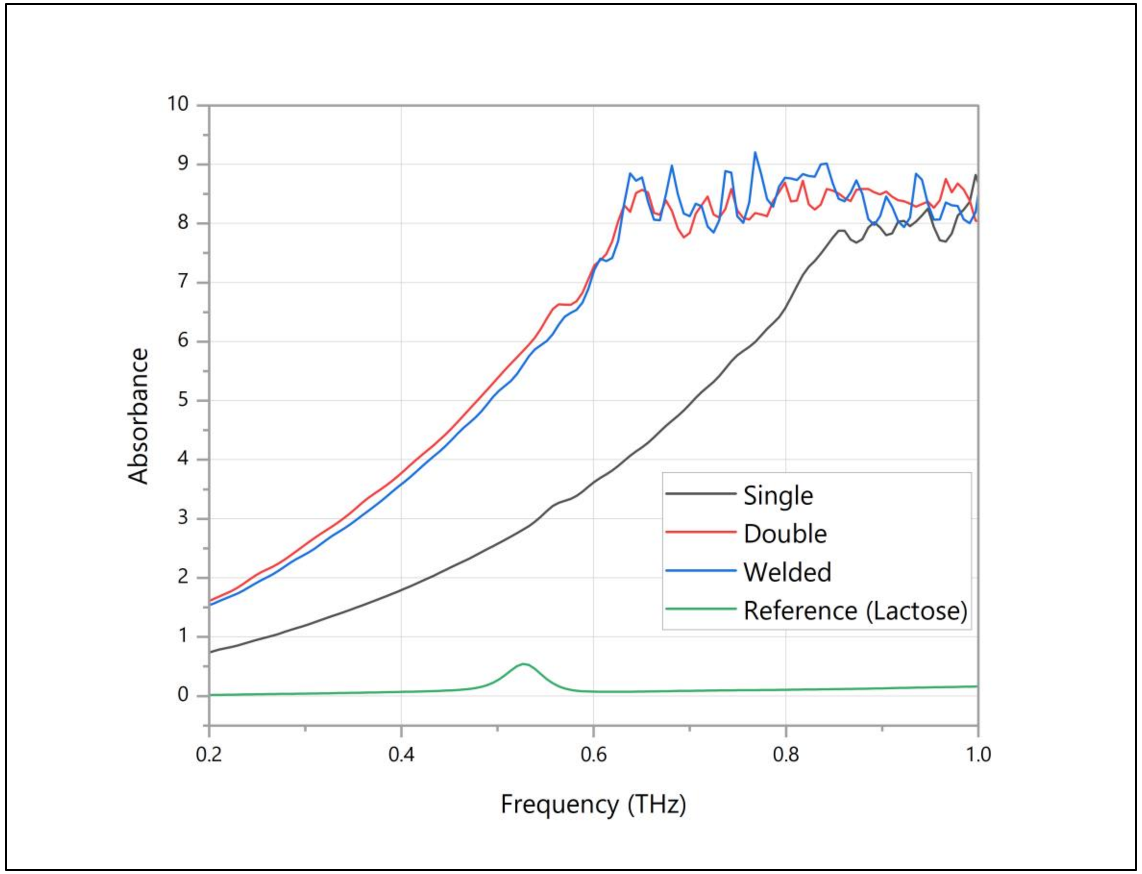


Terahertz Time-Domain Spectroscopy (THz-TDS)

- TPS Spectra 3000 Terahertz Transmission Spectrometer (TeraView Limited, Cambridge, United Kingdom)
- Wide range of terahertz radiation: **60 GHz to 3 THz (2 cm^{-1} to 100 cm^{-1})**
- Scans at a rate of **30 scans per second** – with a **spectral resolution of 32 GHz (1.2 cm^{-1})**

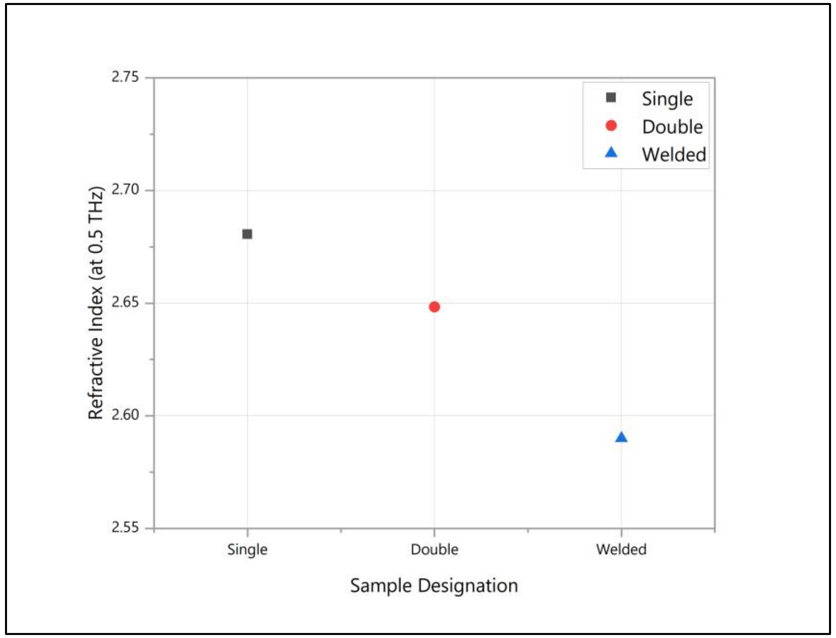
THz Data of Welded Glasses





Laser Welding of Glasses

- Welded glass exhibits **small changes in THz refractive index as well as absorbance** – indicating no major changes in glass structure due to ultrafast laser modification.
- We have **a provisional patent** (No. 63/650,121; Manufacturing Systems and Methods for Welding, Joining, and Other Processing of Glass; 5/21/2024) filed with partnering industry.



Overall Summary

- Ultrafast lasers **show promise** as disruptive glass welding technology for value-added processing of glasses.
- With large selection of systems and powers available in the market, technological **development and breakthroughs are feasible**.
- Well-identified laser parameters and datasets are required before implementation in commercial scale. As the cost of these systems continue to decrease, the **glass industries can apply these approaches to increase quality and reduce cost of VIG windows.**

Acknowledgments

- The Sundaram group members: Braeden Clark, Ruhil Dongol, Priyatham Tumurgoti, Karen Bond, Kameron Chambliss, Dan Steere, Sean Locker, David Dobesh, Garrett J. Vander Stouw, Nicolas Tostanoski, Nathan Skeele, Kathleen Matthies, and Nathaniel Marrero

- Faculty and supporting staffs: Inamori School of Engineering and The New York State College of Ceramics

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Thank you for your time!

Any questions or comments?