Laser-Induced Birefringence in Modified Fused Silica: 157-nm and 193-nm Irradiation

V. Liberman, M. Rothschild,
S. T. Palmacci, D. E. Hardy
Lincoln Laboratory, Massachusetts Institute of Technology
Lexington, MA 02420

and

A. Grenville
Intel/SEMATECH

Motivation

- For immersion lithography, the resolution is increased with higher fluid index, which is ultimately limited by the refractive index of the final element
  - At 193 nm: $n(SiO_2) = 1.56$ $n(CaF_2) = 1.50$
  - At 157 nm: $n(F{:}SiO_2) = 1.68$ $n(CaF_2) = 1.56$
- Using modified fused silica as a final element for 157 nm is an attractive possibility
  - High index
  - No intrinsic birefringence
- However, modified fused silica can potentially be damaged by laser irradiation
  - Biggest concern is compaction/rarefaction
- Therefore, we have compared laser-induced birefringence at 193 and 157 nm of modified fused silica

Exposure Setup: 193 nm vs. 157 nm

- For cross-correlation purposes, must carefully consider differences between the two experimental setups

	193-nm	157-nm
Laser	LambdaPhysik A4030	LambdaPhysik A1030
Wavelength	193 nm	157 nm
Beam Size	3 mm diameter, round	
Fluence	2 mJ/cm^2/pulse	
Pulse Duration	11.6 ns (FWHM), 20.6 ns (TIS)	6 ns (FWHM), 29.7 ns (TIS)
Polarization	Vertical (>90%)	Unpolarized
Repetition Rate	1000 Hz and 4000 Hz used	1000 Hz

Metrology

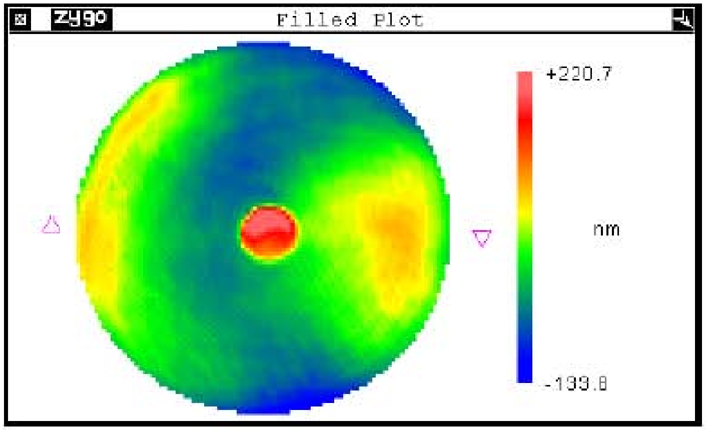
- Interferometric measurement
  - Measured after final exposure
  - Use Zygo MST1550
    Fourier Transform Phase-Shifting Interferometer
- Birefringence measurement and analysis
  - Hinds Exicor 633-nm system
  - Samples removed periodically from exposure setup
  - Initial birefringence subtracted manually

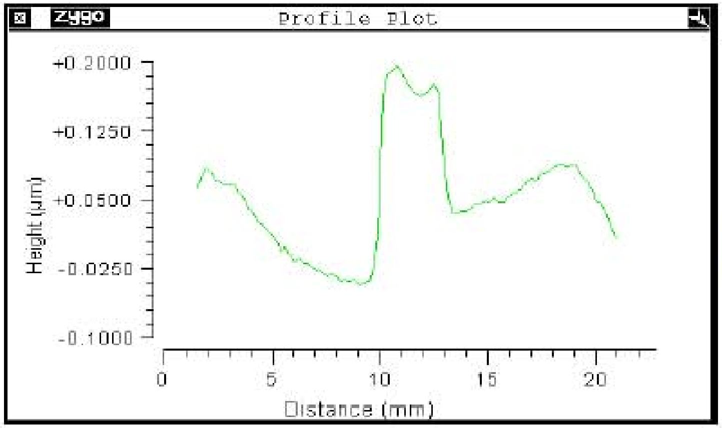
Samples Used in the Study

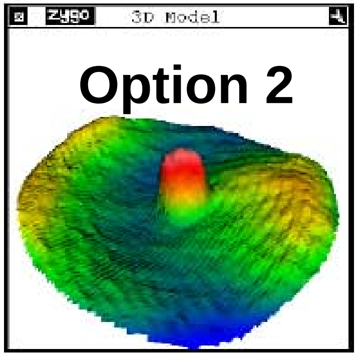
- Modified fused silica samples from Asahi Glass Company
  - Two kinds of material, labeled “Option 2” and “Option 3”
  - Samples are one inch diameter and one inch length

- 193-nm lithography grade fused silica
  - 20x20 mm cross section, 10 cm long

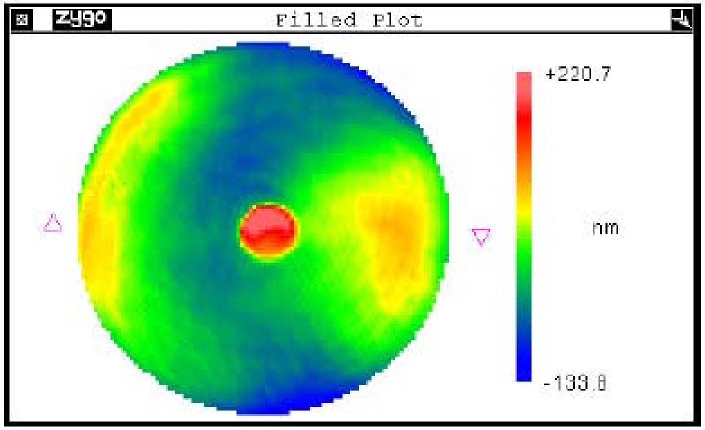
Interferometric Measurements of 157-nm Exposed Samples

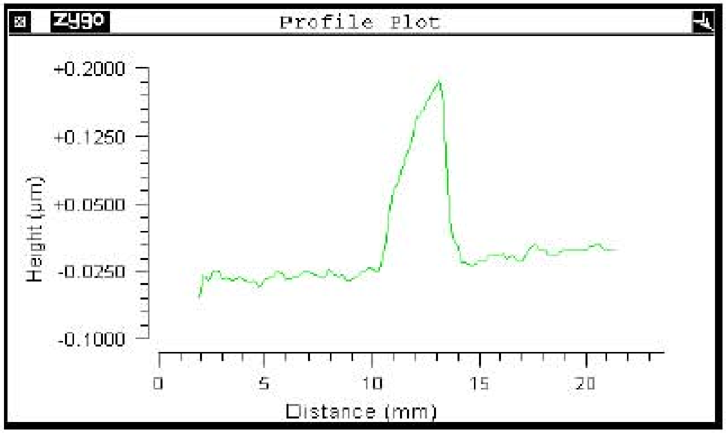


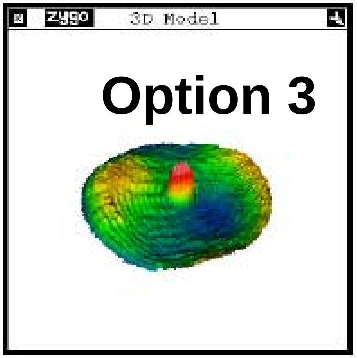




Option 2





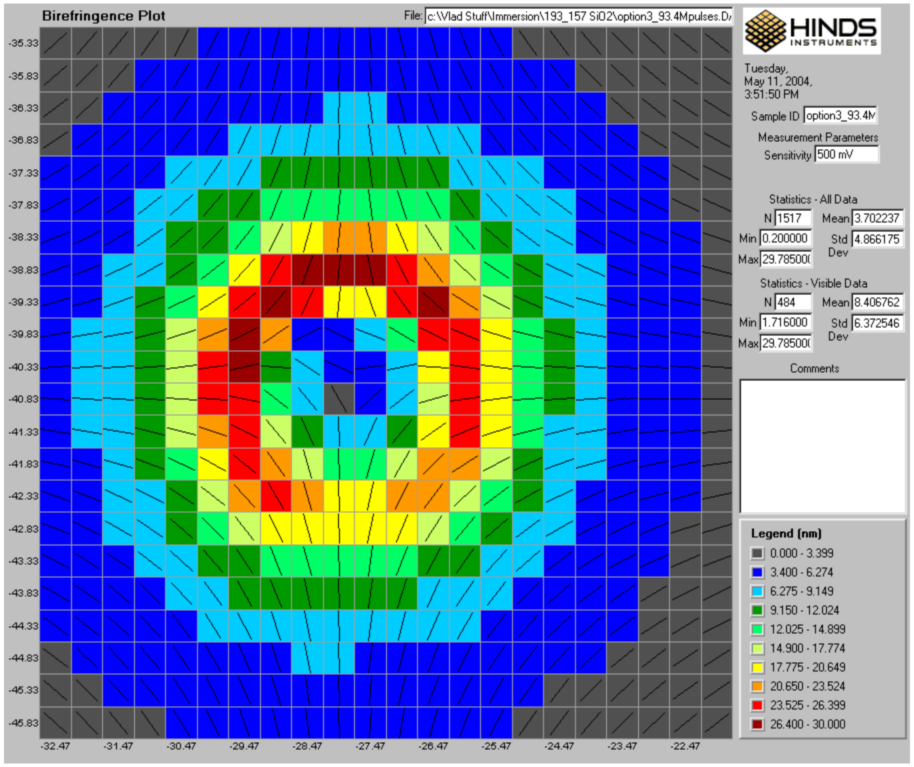


Option 3

- Optical path increases by 10 ppm in irradiated area ➔ Densification
- 2 mJ/cm^2/pulse, 150 Mp

Induced Birefringence Patterns
193 vs. 157 nm

- **157 nm: (Peak = 30 nm after 93 Mp)   193 nm: (Peak = 6 nm after 800 Mp)**



Birefringence Plot

File: c:\Vlad Stuff\Immersion\193_157 SiO2\option3_93.4Mpulses.D

Tuesday,
May 11, 2004,
3:51:50 PM

Sample ID option3_93.4M

Measurement Parameters
Sensitivity 500 mV

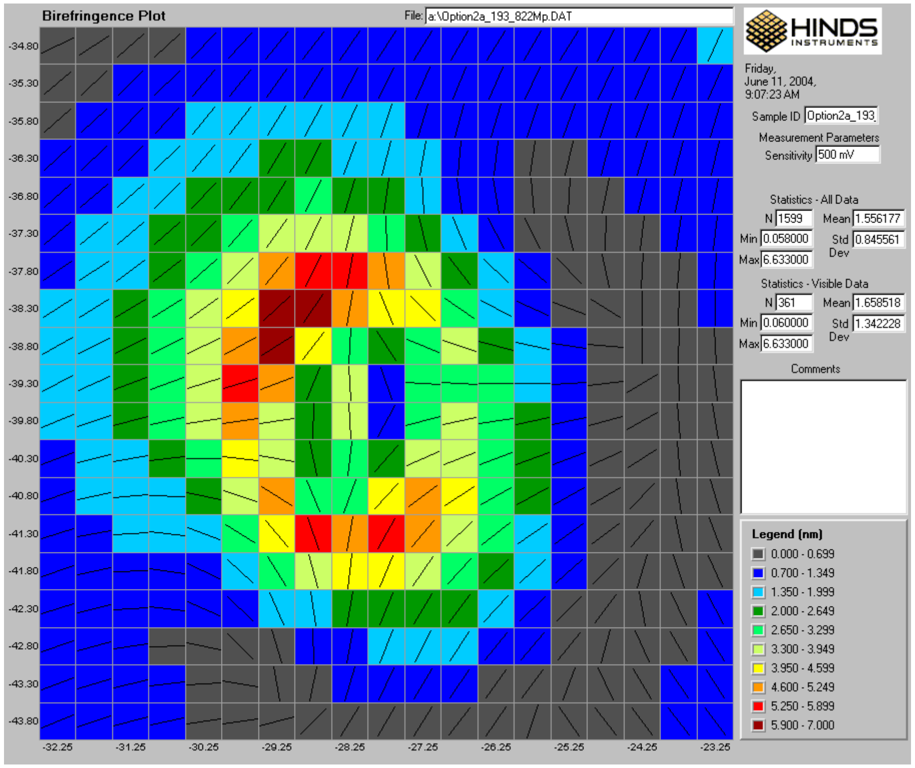
Statistics - All Data
N 1517
Mean 3.702237
Min 0.200000
Std Dev 4.866175
Max 29.78500

Statistics - Visible Data
N 484
Mean 8.406762
Min 1.716000
Std Dev 6.372546
Max 29.78500

Comments

Legend (nm)

⬛	0.000 - 3.399
🟦	3.400 - 6.274
🟦	6.275 - 9.149
🟩	9.150 - 12.024
🟩	12.025 - 14.899
🟩	14.900 - 17.774
🟨	17.775 - 20.649
🟧	20.650 - 23.524
🟥	23.525 - 26.399
🟫	26.400 - 30.000



Birefringence Plot

File: a:\Option2a_193_822Mp.DAT

Friday,
June 11, 2004,
9:07:23 AM

Sample ID Option2a_193

Measurement Parameters
Sensitivity 500 mV

Statistics - All Data
N 1599
Mean 1.556177
Min 0.058000
Std Dev 0.845561
Max 6.633000

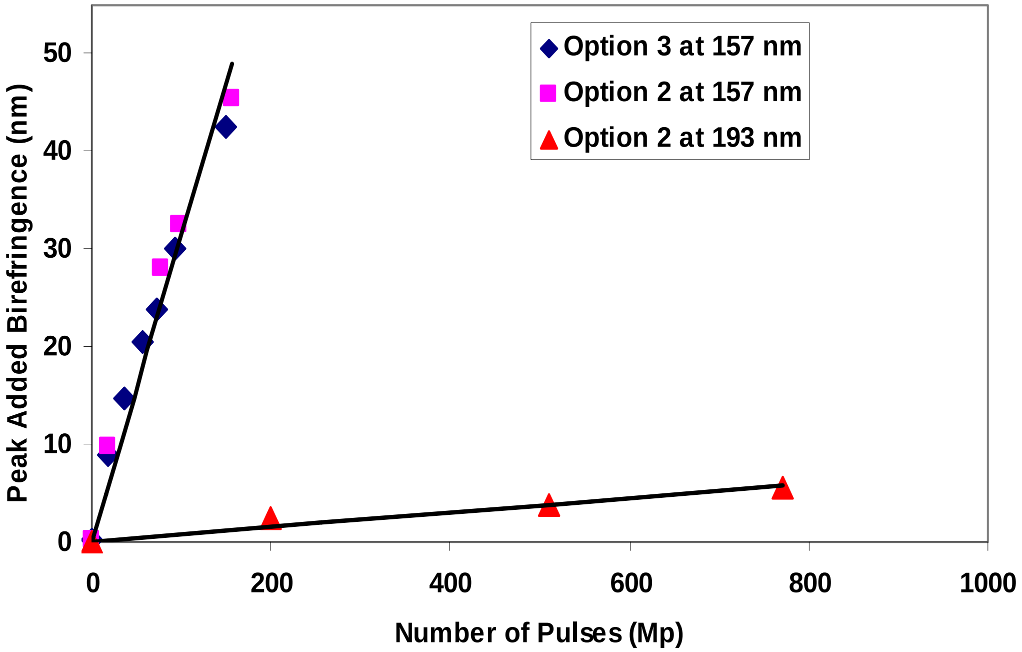
Statistics - Visible Data
N 361
Mean 1.658518
Min 0.060000
Std Dev 1.342228
Max 6.633000

Comments

Legend (nm)

⬛	0.000 - 0.699
🟦	0.700 - 1.349
🟦	1.350 - 1.999
🟩	2.000 - 2.649
🟩	2.650 - 3.299
🟩	3.300 - 3.949
🟨	3.950 - 4.599
🟧	4.600 - 5.249
🟥	5.250 - 5.899
🟫	5.900 - 7.000

Evolution of Peak Birefringence with Pulse Count



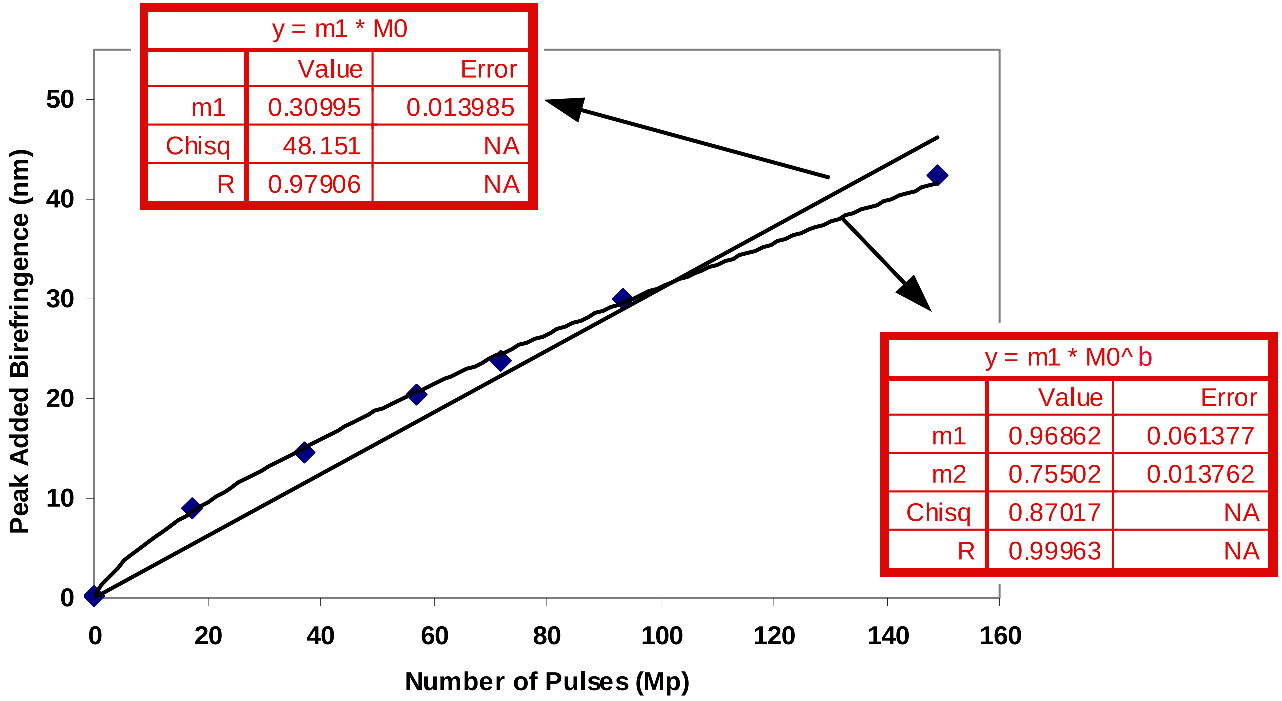
- Lines added to guide the eye (see scaling discussion below)
- No significant difference between “Option 2” and “Option 3” samples for 157-nm exposure

Birefringence Scaling Laws

- 193 nm densification
  - Previous studies indicate two-photon process
    - Scaling as $(NI^2/\tau)^b$, where N = laser pulses, I = laser fluence, τ = pulse duration, "integral-square" definition, $b \approx 0.5 - 0.7$
- 157 nm densification
  - Previously suggested one-photon process, scaling as NI
    - Borrelli, Smith and Allan, Opt. Lett. 24 (1999) 1401.
  - Current material has much higher initial transparency
    - 0.02/cm for current material vs. 1.6/cm for the Borrelli *et al.* material
    - Two-photon process may still be applicable

Scaling of 157-nm Birefringence Data

- **Since both fluence and pulse duration are fixed through the run, the scaling becomes**
  - **$\propto N$ for one-photon process**
  - **$\propto N^b$ for two-photon process**



y = m1 * M0

	Value	Error
m1	0.30995	0.013985
Chisq	48.151	NA
R	0.97906	NA

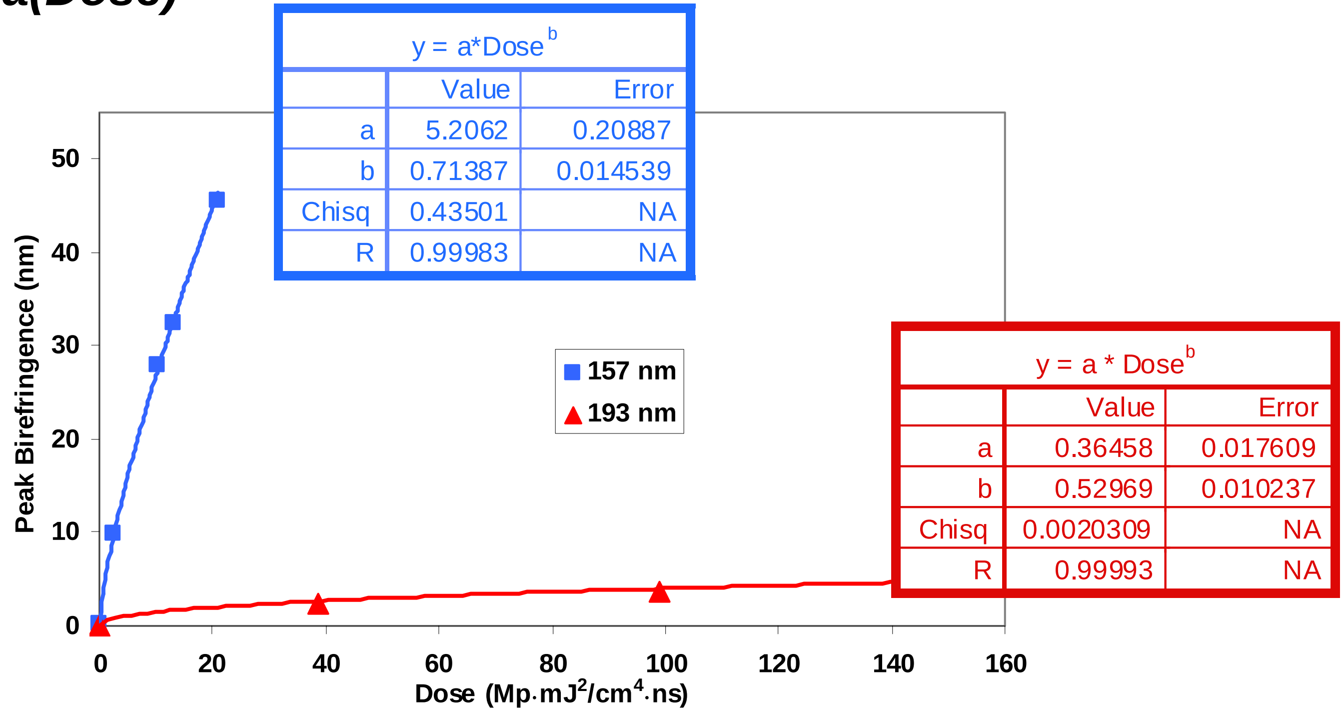
y = m1 * M0^ b

	Value	Error
m1	0.96862	0.061377
m2	0.75502	0.013762
Chisq	0.87017	NA
R	0.99963	NA

⇒ Much better fit quality for a power law, a two-photon process (*b* ~ 0.7)

Birefringence Scaling
157 and 193 nm

- **Two-photon process assumed**
  - ***a(Dose)^b***



y = a*Dose^b

	Value	Error
a	5.2062	0.20887
b	0.71387	0.014539
Chisq	0.43501	NA
R	0.99983	NA

y = a * Dose^b

	Value	Error
a	0.36458	0.017609
b	0.52969	0.010237
Chisq	0.0020309	NA
R	0.99993	NA

- **Note that both *a* and *b* coefficients are different for the two wavelengths**
  - **Fundamental differences in photophysics?**

Lifetime Extrapolation for Birefringence

- Assume 0.2 mJ/cm^2/pulse, 100 Bp lifetime
  - 193 nm: total dose = 200 Mp·mJ^2/cm^4 ·ns

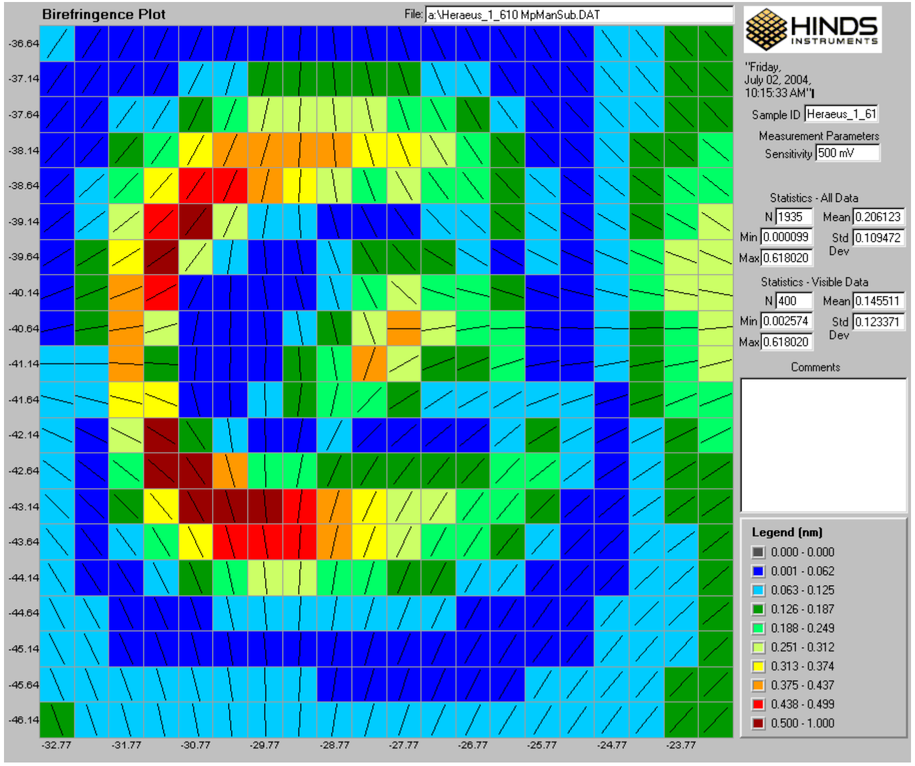
    Lifetime birefringence = 2.5 nm/cm
  - 157 nm: total dose = 135 Mp·mJ^2/cm^4 ·ns

    Lifetime birefringence = 68 nm/cm

- 28X higher lifetime birefringence predicted for 157 vs. 193 nm for F-doped fused silica

193-nm Grade vs. F-doped SiO_2
Similar Scaling Laws

100-mm-thick 193-nm grade



File: a:\Heraeus_1_610 MpManSub.DAT

"Friday,
July 02, 2004,
10:15:33 AM"

Sample ID: Heraeus_1_61

Measurement Parameters
Sensitivity: 500 mV

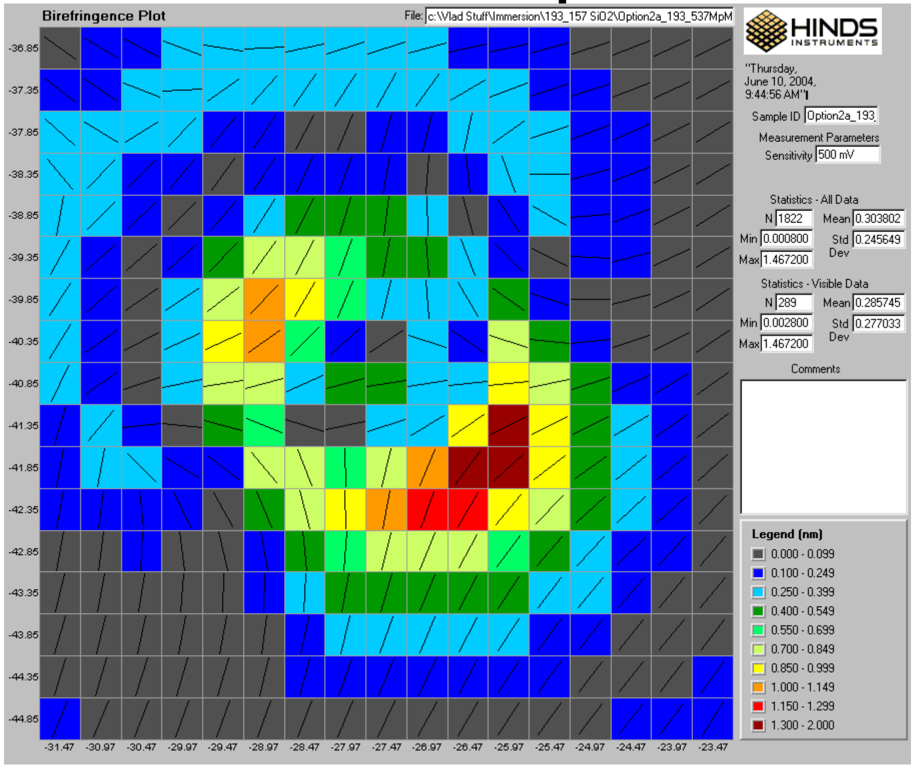
Statistics - All Data
N: 1935
Mean: 0.206123
Min: 0.000099
Std Dev: 0.109472
Max: 0.618020

Statistics - Visible Data
N: 400
Mean: 0.145511
Min: 0.002574
Std Dev: 0.123371
Max: 0.618020

Legend (nm)
⬛ 0.000 - 0.000
🟦 0.001 - 0.062
🟦 0.063 - 0.125
🟩 0.126 - 0.187
🟩 0.188 - 0.249
🟨 0.251 - 0.312
🟨 0.313 - 0.374
🟧 0.375 - 0.437
🟥 0.438 - 0.499
🟫 0.500 - 1.000

- **0.7 mJ/cm²/pulse, 600 Mp**
- **Peak birefring. = 0.6 nm/cm**
- **For *a(Dose)^b*, *b* = 0.7, *a* = 0.09**

25-mm-thick F-doped



File: c:\Vlad Stuff\Immersion\193_157 SiO2\Option2a_193_537MpM

"Thursday,
June 10, 2004,
9:44:56 AM"

Sample ID: Option2a_193

Measurement Parameters
Sensitivity: 500 mV

Statistics - All Data
N: 1822
Mean: 0.303802
Min: 0.000800
Std Dev: 0.245649
Max: 1.467200

Statistics - Visible Data
N: 289
Mean: 0.285745
Min: 0.002800
Std Dev: 0.277033
Max: 1.467200

Legend (nm)
⬛ 0.000 - 0.099
🟦 0.100 - 0.249
🟦 0.250 - 0.399
🟩 0.400 - 0.549
🟩 0.550 - 0.699
🟨 0.700 - 0.849
🟨 0.850 - 0.999
🟧 1.000 - 1.149
🟥 1.150 - 1.299
🟫 1.300 - 2.000

- **2 mJ/cm²/pulse, 600 Mp**
- **Peak birefring. = 1.5 nm/cm**
- **For *a(Dose)^b*, *b* = 0.7, *a* = 0.06**

Conclusions

- Compared laser-induced birefringence
  - F-doped fused silica at 193 vs. 157 nm
  - F-doped vs. conventional fused silica at 193 nm

- 157-nm exposure
  - Primarily densification
  - Two-photon scaling
  - Over a system lifetime, 28 times higher birefringence than at 193 nm is predicted

- 193-nm exposure
  - Rate of generating peak birefringence in modified fused silica comparable to that of conventional fused silica

Acknowledgments

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- We would like to thank Asahi Glass Company for providing F-doped fused silica samples for this study.