Incubation effect dynamics of silicon irradiated by violet and near-infrared ultrashort laser pulses

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Using multiple femtosecond laser pulses to irradiate a sample on the same spot, the ablation thresholds depends on the number of irradiated pulses. The multi-shot ablation threshold can be significantly lower than the single-shot ablation threshold because of the incubation effect [1]. Ultra-high precision nanomilling of copper to depths of several nanometers and post-fabrication bi-direction tuning of silicon microring resonator circuits [2] were demonstrated using multiple femtosecond laser pulses with fluences below the single-shot ablation threshold by taking advantage of the incubation effect. However, the detailed processes for multiple-shot irradiation of a material at fluences well below single-shot ablation threshold is not well understood. In this study, we utilize the silicon microring resonator as a novel tool to better understand the physics of incubation effects.

The refractive index change induced by laser irradiation can be detected with unprecedented sensitivity by measuring the resonant wavelength shift of a silicon microring resonator. In a previous study [4], we have determined the thresholds for refractive index change irradiated with single femtosecond laser pulses at 400 nm and 800 nm wavelengths. The threshold for permanent index change at 400 nm wavelength was determined to be 0.053 J/cm^2 for single-shot irradiation, which agrees with previously reported threshold values for femtosecond laser melting of crystalline silicon. However, the threshold for index change at 800 nm wavelength was found to be 0.044 J/cm^2 for single-shot irradiation, which is five times lower than the previously reported threshold values for visual change on the silicon surface. The discrepancy for 800nm irradiation is attributed to crystalline modifications below the melting temperature that were not observed before. In this study, by irradiating silicon microring resonators with femtosecond laser pulses on the same location at fluences significant below the single shot thresholds for refractive index change, while measuring the shot-to-shot evolution of refractive index changes, information about the dynamics of incubation effects can be obtained. Interestingly, our results indicate that the incubation effects behave significantly differently for irradiation at 400nm wavelength as compared to at 800nm wavelength. The experimental data of shot-to-shot refractive index change for silicon irradiated by ultrashort laser pulses with fluences significantly below the visual damage threshold will be valuable for the development of detailed models for incubation effects.

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[2] Kirkwood, S. E., et al. "Nanomilling surfaces using near-threshold femtosecond laser pulses." Journal of Physics: Conference Series. Vol. 59. No. 1. IOP Publishing, 2007.

[3] Zhang, Ruoheng, et al. "Multi-shot near-infrared femtosecond laser tuning of silicon microring resonators." Optics Communications (2024): 130446.

[4] Bachman, D., et al. "Threshold for permanent refractive index change in crystalline silicon by femtosecond laser irradiation." Applied Physics Letters 109.9 (2016).