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Damage of thin metal films by high-power terahertz pulses

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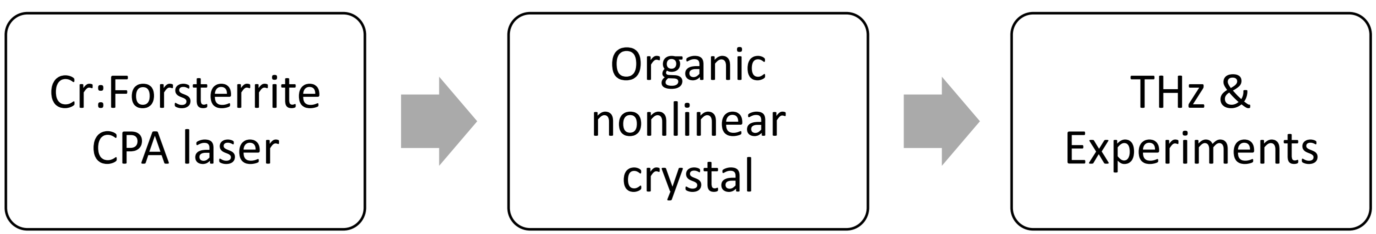
Outline

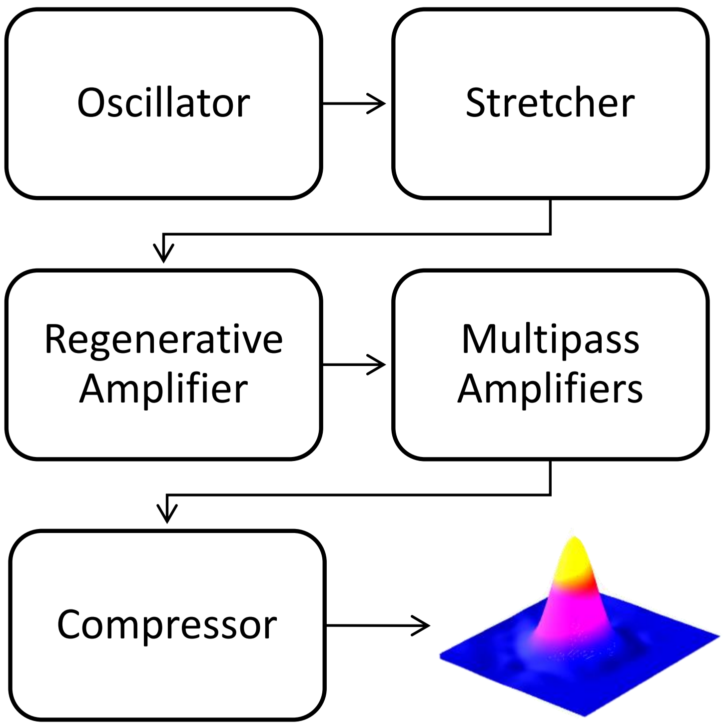
1. Terahertz source
2. Experimental scheme
3. Results

Terahertz source

1. Femtosecond Cr:forsterite laser
2. Organic nonlinear crystal



Femtosecond Cr:forsterite laser



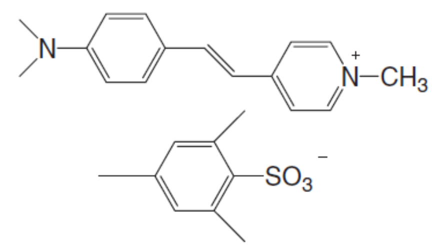
Output characteristics

- Wavelength - 1240 nm
- Pulse duration - 100 fs
- Pulse energy - 20 mJ
- Pulse energy stability - 5%
- Intensity contrast - 10^7
- Repetition rate - 10 Hz
- M^2 - 1.3

Agranat M. B., Ashitkov S. I., Ivanov A. A., Konyashchenko A. V., Ovchinnikov A. V., Fortov V. E.
Terawatt femtosecond Cr:forsterite laser system //
Quantum Electron. 2004. V. 34, No. 6. P. 506–508.

Organic nonlinear crystal

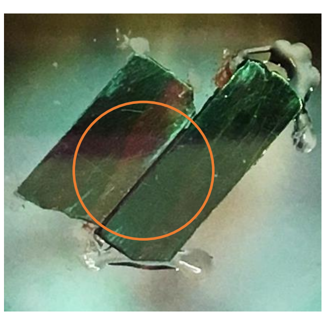
Terahertz Generator: Electro-Optic DSTMS Crystal



DSTMS: 4-N,N-dimethylamino-4’-N’-methyl-stilbazolium 2,4,6-trimethylbenzenesulfonate

Features

- High quality crystal
- Large nonlinear optical susceptibilities
- Phase matching for THz generation between 720 nm and 1650 nm
- Efficient terahertz generation in 0.3-3 THz range @ 1240 nm

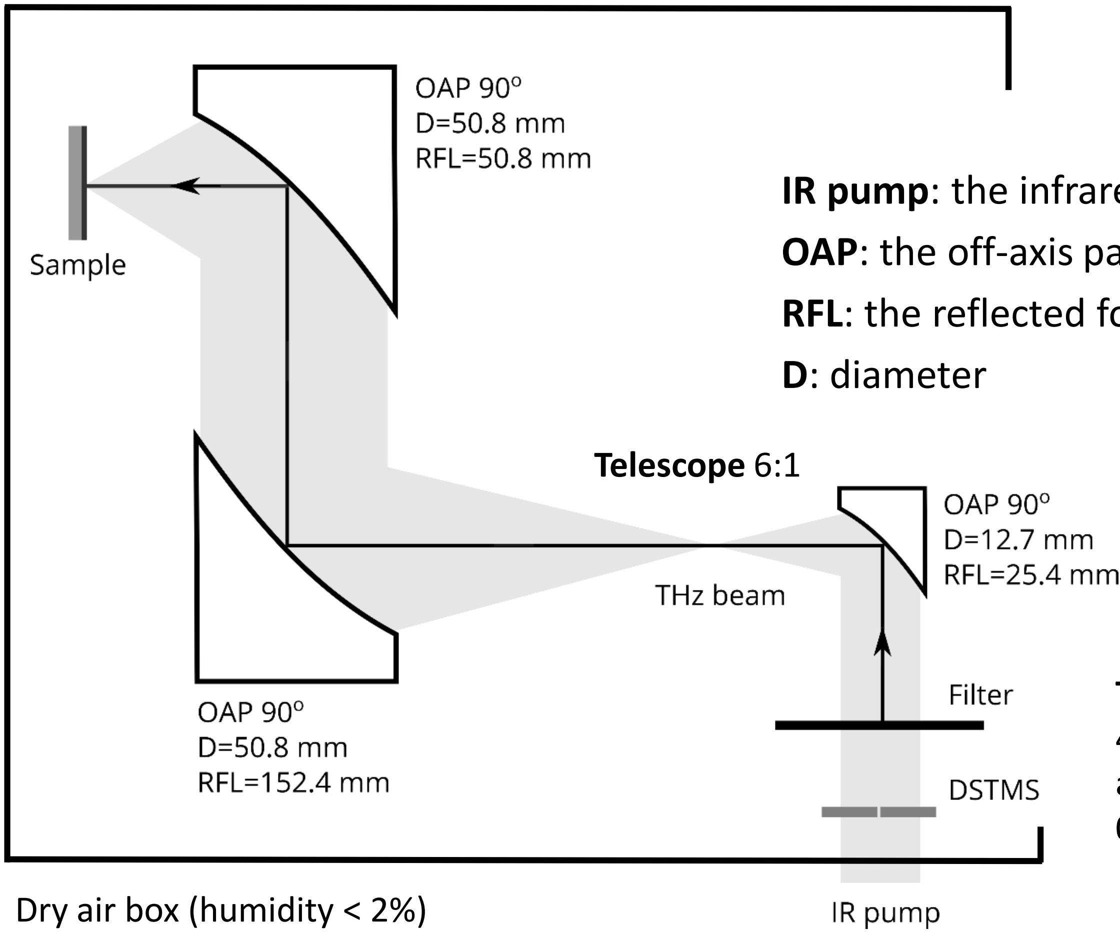


Thickness: 440 μm

Effective diameter: 8 mm

Conversion efficiency: >1%

Experimental scheme



IR pump: the infrared laser pulses at 1.24 μm

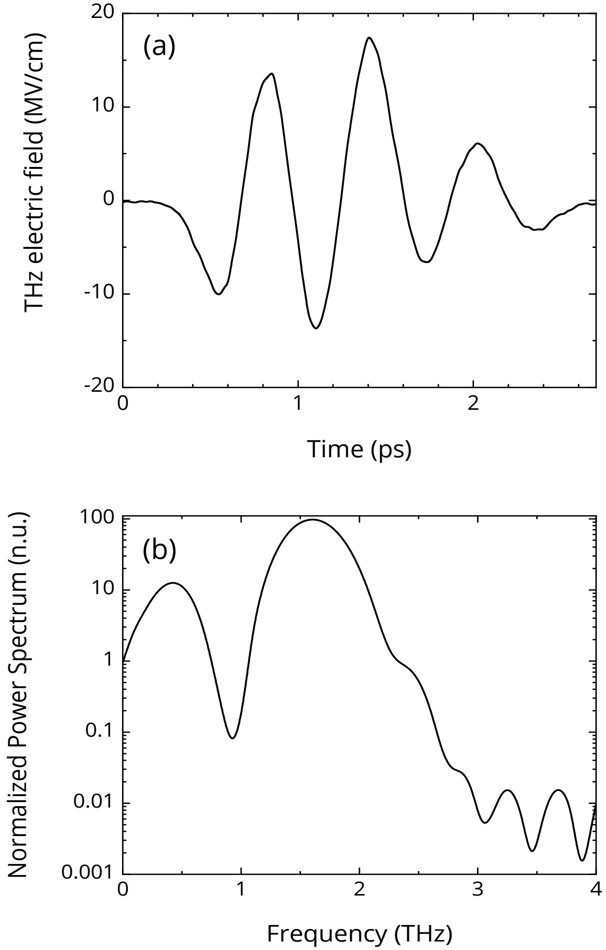
OAP: the off-axis parabolic mirrors

RFL: the reflected focus length

D: diameter

THz low pass filter (LPF8.8-47, Tydex). λ_{cut}-34 μm. The attenuation coefficient @ 0.62-1.24 μm > 10^8.

Experimental scheme



The value of electric-field strength was estimated using the energy of a THz pulse, its duration and a focused to a diffraction-limited spot size, assuming a Gaussian pulse shape:

$$E_{THz}\left[\frac{V}{cm}\right] = 27.45\sqrt{I_{THz}\left[\frac{W}{cm^2}\right]} \qquad (1)$$

$$I_{THz} = \frac{4\sqrt{\ln 2}}{\pi\sqrt{\pi}}\frac{W_{THz}}{\omega^2\tau_{FWHM}} \qquad (2)$$

$$\omega = 2\lambda F/(\pi D) \qquad (3)$$

$\boldsymbol{W_{THz}}$ — the THz pulse energy, $\boldsymbol{\tau_{FWHM}}$ — the THz pulse duration, $\boldsymbol{\omega}$—the Gaussian beam radius at $1/e^2$ level, $\boldsymbol{\lambda}$—the central wavelength of THz spectrum, ***F***—the focal length of the OAP, ***D***—the beam diameter on the OAP.

$\boldsymbol{W_{THz}}$ ~ **110** μJ (measured by a calibrated Golay cell)

$\boldsymbol{\tau_{FWHM}}$ ~**700** fs (measured by a first-order autocorrelator)

$\boldsymbol{\omega_0}$ ~**128** μm (estimated for λ=190 μm (1.58 THz), F=50.8 mm, D=48 mm)

$\boldsymbol{E_{THz}}$ ~ **20** MV/cm

Results

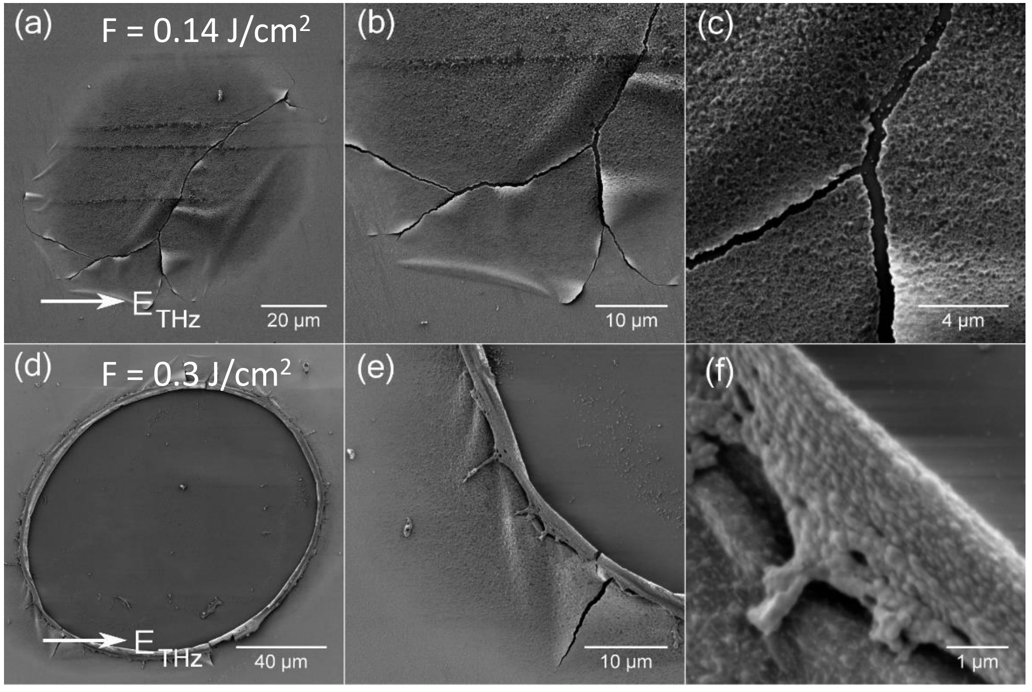
Samples

- 20-nm Al film
- 20-nm Ni film

The samples were a thin metal films deposited on a polished glass substrate of 180 μm in thickness (a coverslip) using magnetron sputtering of a high-clean metal target. The thickness of the magnetron-sputtered films were 20 nm. The study of surface morphology using AFM and SEM revealed surface roughness (R_a) of 4.5 nm.

Results

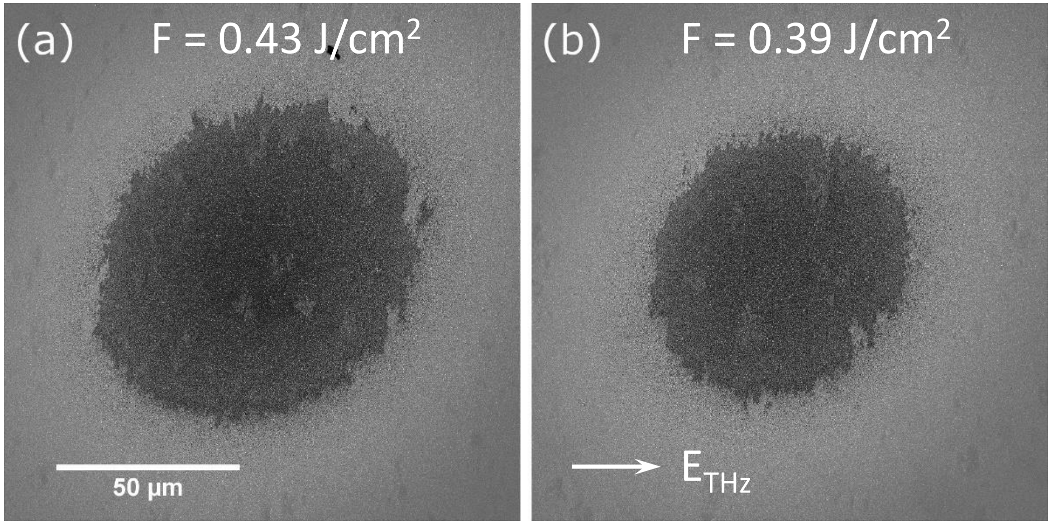
Single shot damage of aluminum film



SEM images of through holes and its edges in **Al film** produced by single THz pulses. (a-c): F = 0.14 J/cm^2; (d-f): F = 0.3 J/cm^2.

Results

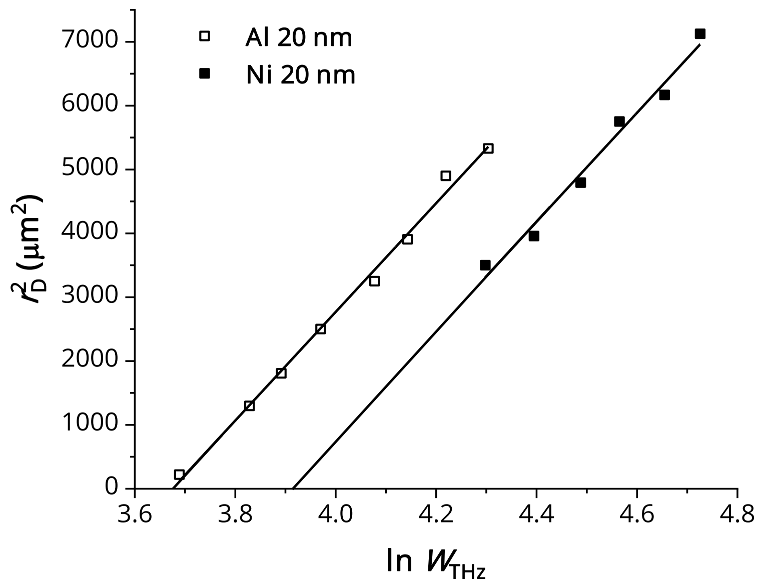
Single shot damage of nickel film



SEM images of **Ni film** damages induced by single terahertz pulse at different fluences. (a): F = 0.43 J/cm^2; (b): F = 0.39 J/cm^2.

Results

The single-pulse damage threshold



Determination of the damage threshold in Al and Ni films irradiated with a single THz pulse; experimental data are shown with square symbols approximated with linear functions (solid lines)

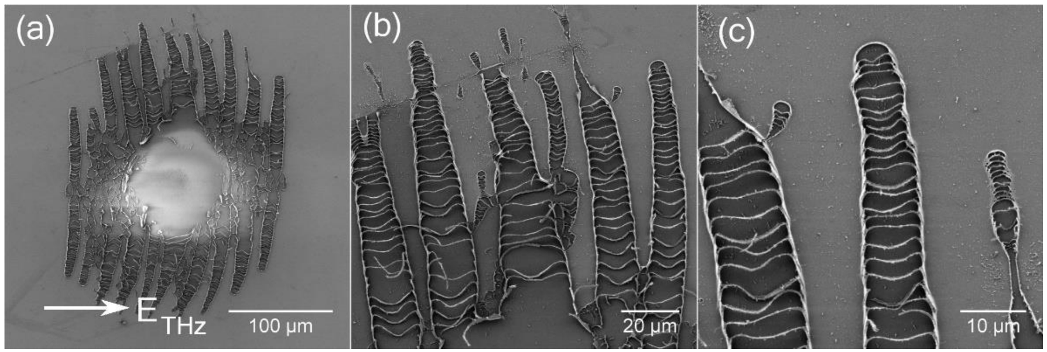
J.M. Liu, Opt. Lett. 7(5), 196 (1982)

The single-pulse damage threshold of the thin film was experimentally determined using a standard technique, where the squared radius (r_D [μm]) of observed damaged regions is plotted versus the logarithm of the energy of incident THz pulses W_{THz} [μJ]. This dependence should be linear for a Gaussian beam. Thus, the threshold energy W_{th} could be derived from the line's intersection with an X-axis, while the line's slope determines the parameter of the Gaussian beam r_0 at the level of 1/e.

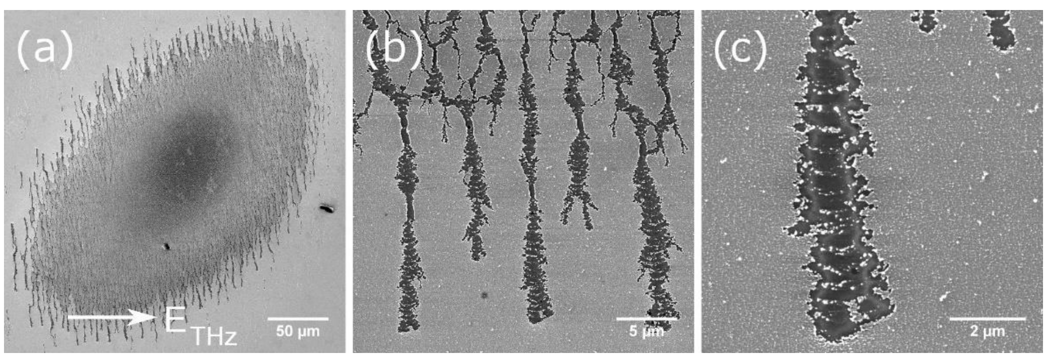
The measured radius r_0 was of 90 μm, which gives a single-pulse damage threshold of the incident fluence of $F_{th} = W_{th}/(\pi r_0^2) \approx$ **0.15 J/cm² for Al** and **0.19 J/cm² for Ni** film at E_{THz}~ **15** MV/cm.

Results

Multiple shot damage of Al and Ni films



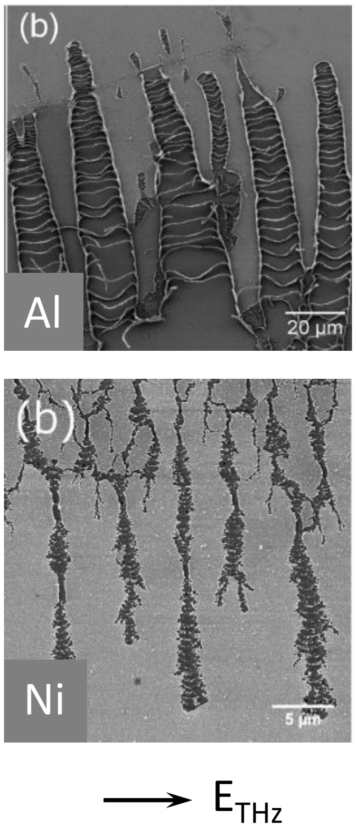
SEM image of Al film damages induced by multiple THz pulses at fluence *F* = 0.24 J/cm^2, *N* = 60.



SEM image of Ni film damage induced by multiple THz pulses at fluence *F* = 0.43 J/cm^2, *N* = 40.

Results

Multiple shot damage of Al and Ni films



Features

1. Damage pattern of Al and Ni films is represented by elongated channels of metal surface discontinuity, aligned perpendicular to the electric filed vector of THz radiation.
2. Damage pattern of Al and Ni films is similar to fractal structure.
3. The channels have cone-shaped (carrot-like) appearance for the Al film.
4. The channels have branched structure (umbrella-type tree) for the Ni film.
5. The channels differ in character and sizes for the Ni and the Al films.

Conclusion

1. Complete destruction of the thin metal films irradiated with a single terahertz pulse has been observed.
2. The single-pulse damage threshold of the thin metal films was measured and determined experimentally.
3. The damage pattern induced by multiple THz pulses has the complex periodic structure in the form of channels on metal film surface that are perpendicular to the in-plane electric field direction of THz radiation.

More details you can find in our publications:

1. Agranat M. B., Chefonov O. V., Ovchinnikov A. V. et al. Damage in a Thin Metal Film by High-Power Terahertz Radiation // Phys. Rev. Lett. 2018. V. 120, P. 085704.
2. Chefonov O. V., Ovchinnikov A. V., Evlashin S. A., Agranat M. B. Damage Threshold of Ni Thin Film by Terahertz Pulses // J Infrared Milli Terahz Waves (2018) 39: 1047.

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