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14. ABSTRACT

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RPPR Final Report
as of 30-Oct-2017

Agency Code:

Proposal Number: 68412ELRIP **Agreement Number: W911NF-16-1-0436**

INVESTIGATOR(S):

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DUNS Number: 041294109 EIN: 160743209
Report Date: 30-Oct-2017 Date Received: 27-Oct-2017
Final Report for Period Beginning 21-Jul-2016 and Ending 30-Jul-2017
Title: Bright THz Instrument and Nonlinear THz Science
Begin Performance Period: 21-Jul-2016 **End Performance Period:** 30-Jul-2017
Report Term: 0-Other
Submitted By: Xi-Cheng Zhang Email: xi-cheng.zhang@rochester.edu
Phone: (585) 275-0333
Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 2 **STEM Participants:** 7

Major Goals: The bottleneck for exploring new cutting-edge research and broader applications, following the significant development of THz science and technology in the late 80's, is the lack of bright, high performance, and cost effective THz sources. Our major goals is to develop a bright THz instrument at The Institute of Optics at the University of Rochester. This instrument provides intense THz pulses with ultra-high peak field for nonlinear THz-matter interaction and spectroscopy.

Accomplishments: One of our most significant achievements under this grant is the achievement of broadband THz wave emission from a thin water film due to short laser pulses excitation. THz wave generation from solids, gases, and plasmas have been demonstrated previously. However, THz wave generation from liquid materials, especially from a polar liquid such as water, has never been reported. For developing bright, high performance and cost effective THz sources, liquid water is a promising choice. As one of the common condensed matter, liquid water has higher molecular density than gas, which could provide a plasma with higher density than one formed from a gas. Additionally, because each laser pulse interacts with a new section of water film, there is no theoretical upper damage threshold as there is in solid crystals. Our results have been published in Applied Physics Letters in August 2017. Our discovery has been highlighted by the American Physics Society's SciLight, Phys.org, Laser Focus World, Photonics Media, and many other public presses.
According to our experimental results, the THz radiation from liquid water shows distinct characteristics as compared to the THz radiation from air plasmas with single color optical excitation. First, the THz field is maximized with longer laser pulse durations. In addition, the p-polarized component of the emitted THz waves will be influenced by the polarization of the optical excitation beam. It is also shown that the energy of the THz radiation is linearly dependent on the excitation pulse energy. Additionally, to control the thickness and stability of the water film, a water control system has been designed and constructed. (See details in the uploaded file.)

Training Opportunities: Nothing to Report

Results Dissemination: Papers published in peer reviewed journals (including submitted)

1. Jin Qi, Yiwen E, Kaia Williams, Jianming Dai, X.-C. Zhang, “Observation of Broadband THz Generation from Liquid water”, Appl. Phys. Lett, 111(7), 071103, (2017).
2. Fabrizio Buccheri, Kang Liu, X.-C. Zhang, “Terahertz Radiation Enhanced Emission of Fluorescence from Elongated Plasmas and Microplasmas in the Counter-propagating Geometry,” Appl. Phys. Lett., 111(9), 091103, (2017).
3. Xuan Sun, Rui Luo, X.-C. Zhang, Qiang Lin, Squeezing the fundamental temperature fluctuations of a high-Q microresonator, Physical Review A 95, (2017), 023822.
4. Xuan Sun, Hanxiao Liang, Rui Luo, Wei C. Jiang, Xi-Cheng Zhang, and Qiang Lin, "Nonlinear optical oscillation dynamics in high-Q lithium niobate microresonators," Opt. Express 25, 13504-13516 (2017)
5. A.P. Shkurinov, A.S. Sinko, P.M. Solyankin, A.V. Borodin, M.N. Esaulkov, V.V. Annenkov, I.A. Kotelnikov, I.V. Timofeev, X.-C. Zhang, Impact of the dipole contribution on the terahertz emission of air-based plasma induced by tightly focused femtosecond laser pulses, Physical Review E 95, (2017), 043209.
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7. L.L. Zhang, T. Wu, H. Zhao, C. Zhang, W. Jin, X.-C. Zhang, Enhanced THz-to-IR emission from gas-surrounded metallic nanostructures by femtosecond laser irradiation, Optics Communications, 381, (2016), 414-417.
8. Y.A. Kapoyko, A.A. Drozdov, S.A. Kozlov, X.C. Zhang, Evolution of few-cycle pulses in nonlinear dispersive media: Velocity of the center of mass and root-mean-square duration, Physical Review A 94 (2016) 9.
9. Anton N. Tcypkin, Sergey E. Putilin, Maksim S. Kulya, et al., Measurement of an extremely large nonlinear refractive index of crystalline ZnSe at terahertz frequencies by a modified Z-scan method, Optical Express, submitted.
10. L.L. Zhang, S.J. Zhang, R. Zhang, T. Wu, Y.J. Zhao, C.L. Zhang, and X.-C. Zhang, “Excitation-Wavelength Dependent Terahertz Wave Polarization Control in Laser-Induced Filament,” Optica, (2017). Submitted
11. Liangliang Zhang, Cunlin Zhang and X.-C. Zhang, “Bi-directional terahertz-to-infrared emission from metal-coated nanostructures upon femtosecond laser irradiation,” Optical Express, submitted.
12. Klarskov, Pernille, Tarekegne, Abebe T., Iwaszczuk, Krzysztof, Zhang, X. C., & Jepsen, Peter, Amplification of resonant field enhancement by plasmonic lattice coupling in metallic slit arrays, Scientific Report, 6 (2016) 37738.

Conference Proceedings

a. Presentations at meetings, but not published in conference proceedings

1. “Broadband Terahertz Wave Generation from Water Film”, Qi Jin, Yiwen E, Kaia Williams, Jianming Dai and X. -C. Zhang, IRMMW, Cancun, Mexico, August 27, 2017.
2. “Terahertz Wave Generation from Liquid Water,” Qi Jin, Kaia Williams, Yiwen E, Jianming Dai and X. -C. Zhang, THz Bio Conference, Oct. 4, 2017.
3. “THz Wave Emission from Water,” Yiwen E, Qi Jin, Kaia Williams, Jianming Dai and X. -C. Zhang, RJUSE TeraTech, Troy, Rensselaser Polytechnic Institute, New York, USA, Oct. 1, 2017.
4. “THz Science, Technology, and Applications,” X.-C. Zhang, Beihang University, Beijing, China, Oct. 19, 2017.
5. “From Speculation to Demonstration: THz Wave Emission from Water,” Physics Department, Capital Normal University of Beijing, Beijing, China, June 19, 2017.
6. “Let light shine out of darkness” Princeton International School of Math and Sciences, Princeton, NY, May 12, 2017.
7. “THz: Imaging Beyond Light” Open Readings 2017, 60th International Conference for Students of Physics and Natural Sciences, Vilnius, Lithuania, March 15, 2017.
8. “The Institute of Optics, A jewel in the crown,” Academy of Opto-Electronics, Chinese Academy of Science, Beijing, China, Dec. 27, 2016.
9. “The Institute of Optics, Micro-Plasma and Extreme THz Science,” Jiliang University, Nov. 8, 2016.
10. “Extreme THz Science,” Westlake Photonics Symposium, Zhejiang University, Hangzhou, China, Nov. 7, 2016.
11. “Enhanced terahertz wave emission from air-plasma tailored by abruptly autofocusing laser beams,” 8th ISUPTW, Chongqing, China, Oct. 11, 2016
12. “The State of The Institute of Optics,” New Graduate students town hall meeting, The Institute of Optics, University of Rochester, September 14, 2016.
13. “Vision” Hong Kong University of Science and Technology, Hong Kong, September 6, 2016.

b. Non-peer-reviewed conference proceeding publications

1. Q. Jin, Y. E, K. Williams, J. Dai, X.-C. Zhang, Observation of Broadband Terahertz Wave Generation from

Liquid Water, Nonlinear Optics, Optical Society of America, Waikoloa, Hawaii, 2017, pp. NW3A.1.
2. Y.V. Grachev, X. Liu, A.N. Tsypkin, S.E. Putilin, V.G. Bespalov, S.A. Kozlov, X.C. Zhang, THz sliced broadband continuum for wireless data transfer with CdSe-CdS modulator, 2016 41st International Conference on Infrared, Millimeter, and Terahertz waves (IRMMW-THz), 2016, pp. 1-2.

Honors and Awards: 2016-2018 X.-C. Zhang, Scientific Advisor, Capital Normal University of Beijing, China
2017 Kang Liu, Rochester Precision Optics Award for Outstanding Graduate Projects
2017 X.-C. Zhang, Australian Academy of Science Selby Fellow, Australia
2016 Fabrizio Buccheri, Rochester Precision Optics Award for Outstanding Graduate Projects

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: PD/PI
Participant: Xi-Cheng Zhang
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Yiwen EE
Person Months Worked: 2.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

CONFERENCE PAPERS:

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: Nonlinear Optics
Date Received: 27-Oct-2017 Conference Date: 17-Jul-2017 Date Published: 17-Jul-2017
Conference Location: Waikoloa, Hawaii
Paper Title: Observation of Broadband Terahertz Wave Generation from Liquid Water
Authors: Q. Jin, Y. E, K. Williams, J. Dai, X.-C. Zhang
Acknowledged Federal Support: **N**

RPPR Final Report
as of 30-Oct-2017

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: Frontiers in Optics
Date Received: 27-Oct-2017 Conference Date: 17-Oct-2016 Date Published: 17-Oct-2016
Conference Location: Rochester, New York
Paper Title: Enhancing THz radiation from two-color laser-induced air-plasma by using abruptly autofocusing beams
Authors: K. Liu, A.D. Koulouklidis, D.G. PAPAZOGLOU, S. Tzortzakis, X.-C. Zhang
Acknowledged Federal Support: **Y**

Bright THz Instrument and Nonlinear THz Science

Final Progress Report

Report Period: 07/21/2016--07/30/2017
Grant Contract #: W911NF1610436

Principal Investigators: **X.-C. Zhang**

The Institute of Optics

University of Rochester

275 Hutchison Road, Rochester, New York 14627

zhangxc@rochester.edu

Authors: Yiwen E and Xi-Cheng Zhang

University of Rochester

Submitted: Dr. Joe Qiu, ARO

Abstract: One of our most significant achievements under this grant is the achievement of broadband THz wave emission from a thin water film due to short laser pulses excitation. THz wave generation from solids, gases, and plasmas have been demonstrated previously. However, THz wave generation from liquid materials, especially from a polar liquid such as water, has never been reported. For developing bright, high performance and cost effective THz sources, liquid water is a promising choice. As one of the common condensed matter, liquid water has higher molecular density than gas, which could provide a plasma with higher density than one formed from a gas. Additionally, because each laser pulse interacts with a new section of water film, there is no theoretical upper damage threshold as there is in solid crystals. Our results have been published in Applied Physics Letters in August 2017. Our discovery has been highlighted by the American Physics Society's SciLight, Phys.org, Laser Focus World, Photonics Media, and many other public presses.

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1. Publications, Presentation and Honors

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c. Honor and Awards

2016-18	X.-C. Zhang, Scientific Advisor, Capital Normal University of Beijing, China
2017	Kang Liu, Rochester Precision Optics Award for Outstanding Graduate Projects
2017	X.-C. Zhang, Australian Academy of Science Selby Fellow, Australia
2016	Fabrizio Buccheri, Rochester Precision Optics Award for Outstanding Graduate Projects

2. Personnel Metrics

Please complete the below tables, providing the information for this reporting period only. Add rows as needed.

1. Graduate Students

Name	Discipline	Percent Supported
Kang Liu	Optics	0%
Qi Jin	Optics	0%

2. Post Doctorates

Name	Percent Supported
Yiwen E	0%
Rui Wang	0%

3. Faculty

Name	National Academy Member	Percent Supported
Xi-Cheng Zhang		0%

4. Undergraduate Students

Name	Discipline	Percent Supported
Kaia Williams	Optics	0%

5. Other Staff

Name	Percent Supported
None	

3. Graduating Undergraduate Metrics

Please provide a count for each category below for **Graduating Undergraduates** that were funded by this project and graduated during this reporting period.

Category	Number of Undergraduates
Number who graduated during this period	0
Number who graduated during this period with a degree in science, mathematics, engineering or technology fields	0
Number who graduated during this period and will continue to pursue a graduate of Ph.D. in science, math, engineering, or technology fields	0
Number who achieved a 3.5 GPA to 4.0 (4.0 max scale)	0
Number funded by a DoD Funded Center of Excellence grant for Education, Research and Engineering	0
Number who intend to work for the Department of Defense	0
Number who will receive scholarships or fellowships for further studies in science, math, engineering, or technology fields	0

4. Masters Degrees Awarded

Please complete the following table, adding rows as necessary.

Name	Discipline
N/A	

5. Ph.Ds Awarded

Please complete the following table, adding rows as necessary.

Name	Discipline
Xuan Sun	Optics
Fabrizio Buccheri	Optics

6. Technology Transfer

No technology transfer for this reporting period.

7. Scientific Progress and Accomplishments

(1) Observation of broadband THz generation in liquid water

We experimentally demonstrate the generation of broadband THz waves from liquid water excited by femtosecond laser pulses. A typical THz time-domain spectroscopy (THz-TDS) is applied to generate and detect our THz signals from liquid water. An amplifier laser with 800 nm wavelength, 1 kHz repetition rate and 50 fs pulse duration is used. A gravity-driven wire-guided free-flowing water film acts as the emitter for the THz field. The thickness of the water film can be adjusted by throttling the flow rate of the water to the wireguide. The thickness is measured and calibrated using an optical intensity autocorrelation system and is 170 μm. The laser beam is focused into the water film using a 1-inch focal length parabolic mirror.

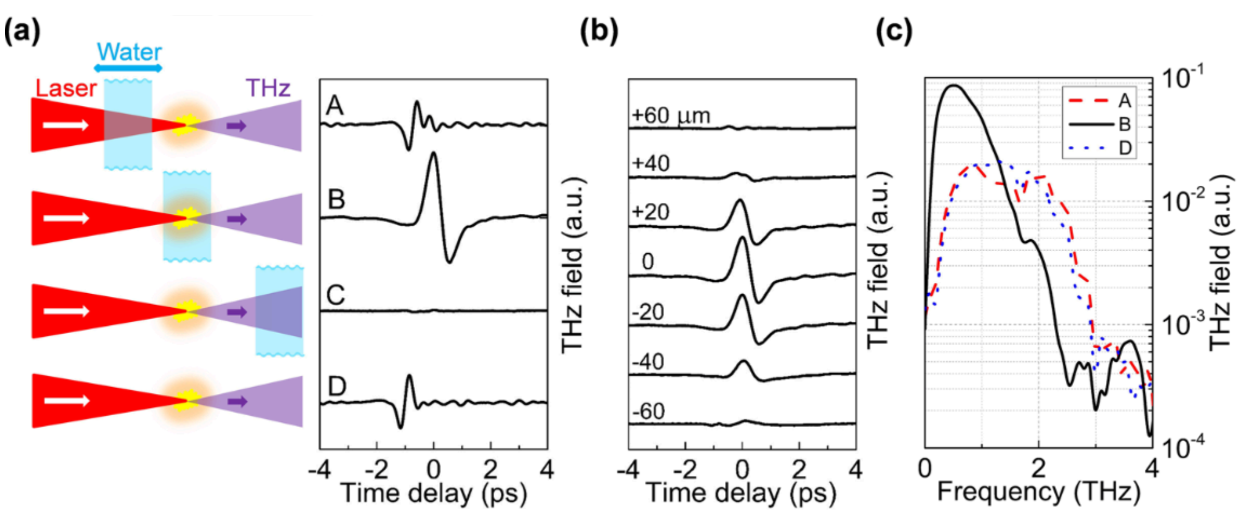

FIG. 1. Measurements of the THz fields when the water film is translated along the direction of laser propagation. (a) THz waveforms are plotted from curves A–C when the water film is before, near, and after the focus, respectively. (b) THz waveforms when the water film is moved near the focal point. (c) Comparison between the THz field from water and that from air plasma in the frequency domain.

By scanning the water film along the optical axis, THz radiation from different sources can be clearly differentiated. The timing distinctions in the waveforms in Fig. 1(a) are of different generation sources. A time delay is observed from the THz waveform from liquid water compared with other generations. Figure 1(b) shows the measurements of THz waveforms as the water film is tracked along the direction of laser propagation marking a relative position across -60 μm to +60 μm. The measurement shows that the emitted THz waves are significantly sensitive to the relative position between the water film and the focus. A comparison of the THz waveforms from liquid water and air plasma is shown in Fig. 1(a). In this measurement, the THz field from the water film is 1.8 times stronger than that from the air plasma. The corresponding comparison in the frequency domain is shown in Fig. 1(c). The measured bandwidth can be limited by the stretch of the probe laser pulses. The measured THz radiation from the water has more low-frequency and less high-frequency components.

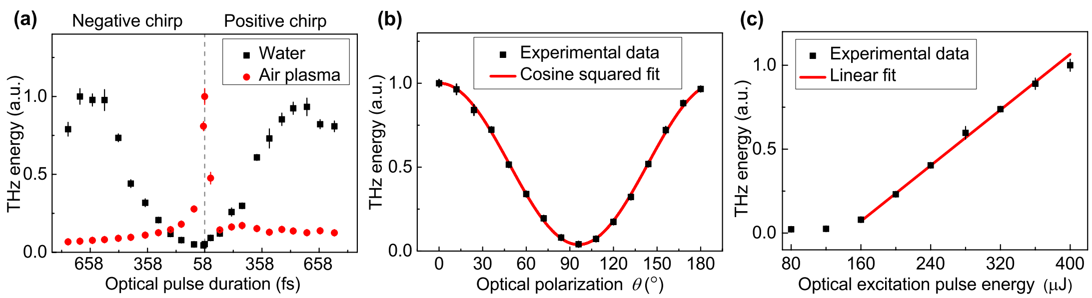

FIG. 2. (a) Normalized THz energy from liquid water and air plasma with different pulse durations of the laser beam. (b) The energy of P-polarized THz field from liquid water with different linearly optical polarization. (c) Normalized THz energy from liquid water as a function of incident optical pulse energy.

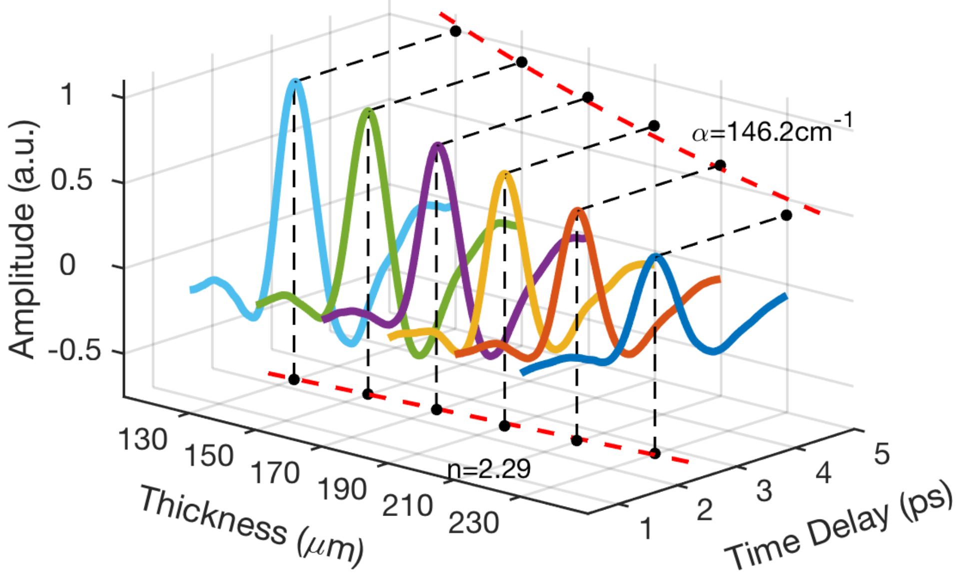

FIG. 3. THz signal with the thickness of water film. Refractive index and absorption coefficient of THz wave in water can be fitted out.

Compared with THz radiation generated from air plasma, the THz radiation from liquid water has a distinct response to various optical pulse durations and shows linear energy dependence upon incident laser pulses. Fig. 2(a) shows normalized THz energy from water and air plasma versus various optical pulse durations. The optical pulse duration is at its minimum of 58 fs when no chirp is applied. It can be observed that unlike the THz radiation from air plasma, where the signal is maximized at a minimum pulse duration with no additional chirp, liquid water generates a maximum field at longer pulse durations. With a longer pulse duration, cascade ionization dominates the process leading an exponential increase in the number of electrons. The THz radiation from liquid water may benefit from higher density of electrons in the water. Fig. 2(b) is shown that strong THz radiation is achieved with a p-polarized (0° and 180°) optical beam, while an s-polarized (90°) optical beam offers sparse contribution. This result goes against the case of single color air plasma THz generation, in which the ponderomotive force is dominantly involved. It is well known that the THz radiation from air plasma with single color optical excitation does not depend upon the polarization of the optical beam, which means the THz radiation energy will keep constant with various optical polarizations. Furthermore, a linear energy dependence observed in Fig. 2(c) is different from the quadratic relation of the single-color air plasma THz generation.

Fig. 3 shows the dependence between THz signal and the thickness of water film. The different colors indicate different thicknesses. Obviously, a thinner film will generate a stronger THz signal. By increasing the thickness from 130 μm to 230 μm, the peak shifts in time domain and amplitude decreases. From this data, the index and absorption coefficient THz radiation in water can be determined, and are 2.29 and 146.2 cm^{-1}, respectively. The results are close to the measurement results for 0.5 THz, which is also the central frequency of our signal.

Our first paper is published in August in the journal Applied Physics Letters. Additionally, when the PI submitted the abstract to IRMMW-THz annual meeting, within 2 minutes, the PI got a reply from the conference chair to congratulate our achievement, and 5 congratulations from 4 countries in two days (they might be the paper evaluators). Now we have received 7 plenary and invited talks at international conferences.

(2) Water film control system and film thickness measurement

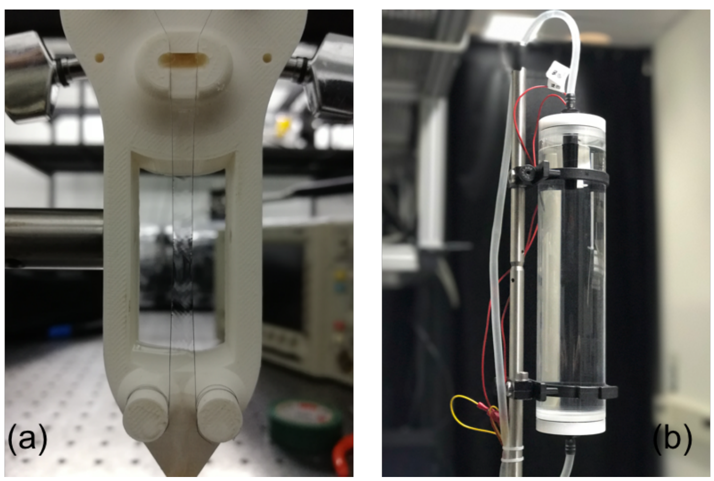

FIG. 4. Water film holder and thickness control system

Fig. 4 shows our self-designed water film holder and thickness control system. From our previous experimental results, we know that the THz signal is very sensitive to the thickness of the water film and the relative position between the laser focus and water film. Precisely controlling the thickness and stability of the water film is another key issue in this study. Fig. 4 (a) shows our water film holder, in which two metal wires are used to guide the water flow. By controlling the flow rate, it can make a thin film with the thickness ranging from 50 μm to 350 μm. The flow velocity is sensitive to the water level in the reservoir, so we add a liquid level switch on the top of the reservoir shown in Fig 4 (b), which connects with a liquid pump to keep the water always in the same level. Additionally, a flow meter is used to measure and control the flow velocity.

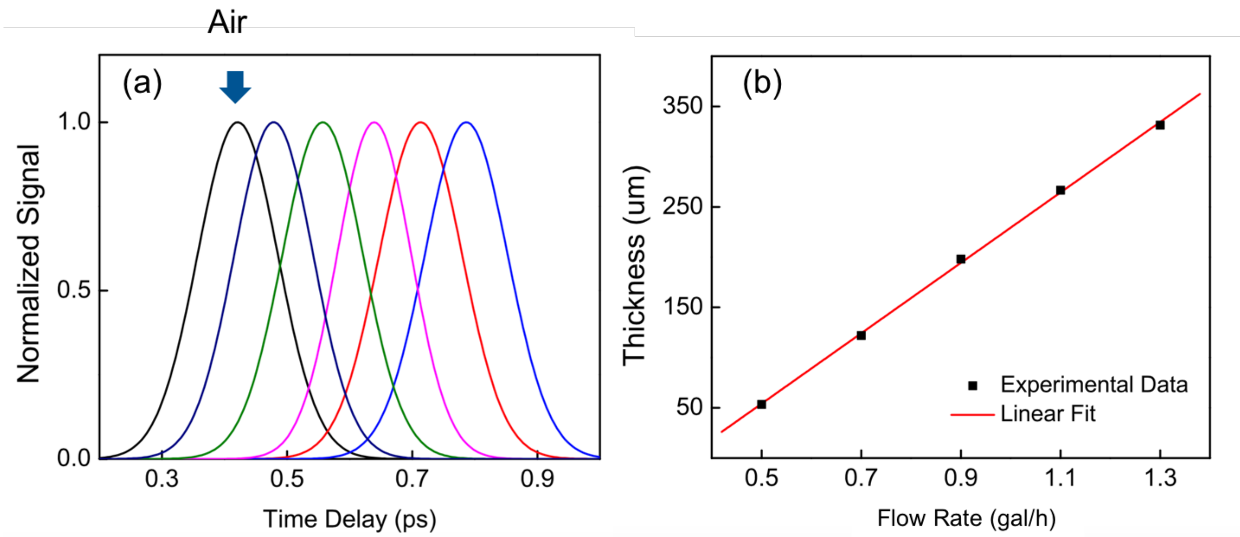

FIG. 5. (a) Autocorrelation results for air and water films with different thicknesses. (b) The calculated relation between thickness and flow rate from the results of (a).

To measure the thickness of the water film, an autocorrelation system is used. Fig. 5 shows the results. The signal from ambient air is used as the reference. When a water film is put in one beam of the autocorrelation system, the signal sees a shift that increases with increased water film thickness. We can then build a linear relation shown in Fig. 5(b) between the thickness and the flow rate.