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14. ABSTRACT
This DURIP project allowed us to obtain the state-of-the-art ultrafast laser system: Libra-F-1K-HE-230: one-box femtosecond amplifier system with 230VAC/50Hz chiller + TOPAS-800-fs (1160-2600nm) + TOPAS-800-fs-UV-2 (240- 1160nm). This system significantly enhanced experimental activities within the Army Research Office research program on Parity-Time Photonic Synthetic Media: From Nonlinear and Singular Optics to Lasing submitted for consideration to the Army Research Office (Principal Investigator Dr. L. Feng, co-PI Dr. N.

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RPPR Final Report
as of 10-Jul-2018

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Begin Performance Period: 15-Aug-2015 **End Performance Period:** 14-Aug-2016
Report Term: 0-Other

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STEM Degrees: 2 **STEM Participants:** 4

Major Goals: Nonlinear optics is focused on the interactions of intense electromagnetic radiation and matter such that the matter responds in a nonlinear manner to the incident radiation fields. It is the emergence of lasers provided optics with sources of such intense coherent radiation and made possible the studies of nonlinear optical phenomena. Therefore, the proposed femtosecond laser system is an essential tool for our studies of novel nonlinear optical materials and nonlinear phenomena in metamaterials. In particular, we proposed three main research thrusts that will rely on the proposed ultrafast optical system:
Thrust 1. Design and demonstrate of meta-atoms that will yield large nonlinearities at optical frequencies aiming at the realization of low-loss materials with large nonlinear coefficients. The proposed OPerA Solo + Libra system will be used to characterize macroscopic samples built of such meta-atoms.
Thrust 2. Exploit the synergy between unique linear and nonlinear properties of metamaterials for the realization of low-power, low-loss, compact, and broadband platforms for high-efficiency nonlinear optical interactions and develop all-dielectric nonlinear graded-index metamaterials and metasurfaces for wavelength conversion and structured light manipulation.
Thrust 3. Design active guided-waves structures, including positive-negative index couplers and parity-time-structures with gain based on nonlinear optical processes of optical parametric amplification and stimulated Raman scattering. In particular, the large Kerr and Raman gain coefficient of silicon will be used to achieve tunable parity-time-based functionalities requiring low pump powers.

Accomplishments: We acquired and installed the state-of-the-art femtosecond laser system in a portable cleanroom environment.

This system is/was used in several DoD-supported studies, including current ARO-supported project “Novel Materials and Structures for Nonlinear Optics” (W911NF1510146), current ARO-supported project “Light Filamentation Science” FY 2011 Multidisciplinary University Research Initiative Program (MURI) add-on (W911NF-11-0297), completed ARO-supported project “Nonlinear Topological Surface States in Meta-Crystals” (W911NF1610270), current ARO-supported project “Parity-Time Photonic Synthetic Media: From Nonlinear and Singular Optics to Lasing” (W911NF1510152), current ONR-supported project “Nonlinear Light-Metasurface Interactions in the Mid-Infrared Range” (N000141613020), and completed DOE-funded project “Structured Light-Matter Interactions Enabled by Novel Photonic Materials” (DESC0014485).

Training Opportunities: Two postdocs and eight graduate students have been trained to use the new fs system. We arranged two one-day training sessions taught by the Coherent Inc. technical support engineer.

Results Dissemination: This system is/was used in several DoD-supported studies, including current ARO-supported project “Novel Materials and Structures for Nonlinear Optics” (W911NF1510146), current ARO-supported project “Light Filamentation Science” FY 2011 Multidisciplinary University Research Initiative Program (MURI) add-on (W911NF-11-0297), completed ARO-supported project “Nonlinear Topological Surface States in Meta-Crystals” (W911NF1610270), current ARO-supported project “Parity-Time Photonic Synthetic Media: From Nonlinear and Singular Optics to Lasing” (W911NF1510152), current ONR-supported project “Nonlinear Light-Metasurface Interactions in the Mid-Infrared Range” (N000141613020), and completed DOE-funded project “Structured Light-Matter Interactions Enabled by Novel Photonic Materials” (DESC0014485). The results of these experiments will be/were reported publications resulting from these projects.

Honors and Awards: School of Engineering and Applied Sciences Senior Researcher of the Year Award (2015)

Protocol Activity Status:

Technology Transfer: Nothing to Report

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Project Contribution:
International Collaboration:
International Travel:
National Academy Member:
Other Collaborators:

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Project Contribution:
International Collaboration:
International Travel:
National Academy Member:
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Project Contribution:
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International Travel:
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Project Contribution:
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Project Contribution:
International Collaboration:
International Travel:
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Date Received: 16-Feb-2017 Conference Date: 31-Aug-2016 Date Published: 31-Aug-2016
Conference Location: San Diego
Paper Title: All-dielectric meta-crystals with topologically protected edge-states
Authors: Mikhail I. Shalaev, Sameerah Desnavi, Wiktor T. Walasik, Natalia M. Litchinitser
Acknowledged Federal Support: **Y**

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Paper Title: Light-matter interactions in engineered optical media
Authors: Natalia, Litchinitser, Wiktor, Walasik, Salih, Silahli
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Authors: Light-Matter Interactions in Engineered Optical Media
Acknowledged Federal Support: **Y**

FINAL REPORT

Natalia Litchinitser

DURIP: Femtosecond Laser System for Nonlinear Optics in Metamaterials

US Army Research Office Award W911NF1510427

Total Award Amount: $300,000

Report Period Begin Date: 08/15/15, Report Period End Date: 08/14/16

This DURIP grant supported acquisition of the state-of-the-art femtosecond laser system with the following properties:

1) Space-efficient one box design Ti:Sapphire oscillator/amplifier system containing the oscillator, amplifier, and kHz class pump laser.

2) The system can deliver < 100fs ultrafast pulses with energy >4.0mJ at a repetition rate of 1kHz and nominal wavelength of 800nm.

3) The system has the option of being configured to deliver < 100fSec pulses of >0.4mJ at a repetition rate of 10kHz and nominal wavelength of 800nm.

4) The system delivers pulse energy stability of <0.5% rms over an 8-hour period. Therefore, the laser system is based on all-solid-state pump technology.

5) The system delivers Gaussian spatial mode profile specified at 800 nm to be TEM_{00} with M^2 < 1.3. Therefore, the laser system must use a regenerative amplifier design.

6) The Ti:Sapphire oscillator/amplifier system utilizes a thermally-stabilized regenerative cavity to comfortably meet long-term stability specifications. Water cooling of the entire laser system is not necessary, and is in fact, not desired due to the much more complex cooling required to cool the entire laser system with water.

7) Since the stability of the amplifier is highly dependent upon the stability of the oscillator, the laser system is seeded by a completely-sealed, hands-free, compact solid-state femtosecond Ti:Sapphire oscillator with integrated pump laser.

The laser system is composed of the following components:

1) **Vitesse 800** modelocked Fixed Wavelength Titanium:Sapphire Seed Oscillator with Integrated Low-Noise Solid-State Pump Laser
2) **Revolution-30** Pulsed Amplifier Solid-State Pump Laser
3) **Libra-F-HE**- Thermally Stablied Regenerative-Cavity Amplifier with Stretcher and Compressor
4) Two **TOPAS-800-FS** Optical Parametric Amplifiers

Specifications of Modelocked Fixed Wavelength Titanium:Sapphire Laser Oscillator with Integrated Low-Noise Solid-State Pump Laser

Performance and Capabilities:

Bandwidth	>10nm at nominal 800nm
Average power	>200 mW @ 800nm (using 2W solid state pump)
RMS noise	< 0.1% (10Hz-20MHz)
Stability	+/- 1% (measured over 2 hours)
Polarization	Horizontal
Repetition Rate	80MHz

Specifications of Pulsed Solid-State Ti:S Amplifier Pump Laser

Performance and Capabilities:

Wavelength	527nm
Pulse Repetition Rate	1kHz
Pulse Energy	>20mJ @ 1kHz
>6mJ @ 5kHz	

Pulse Energy Stability <1% rms over 8 hour period

- The system must be based on diode-pumped technology in order to ensure long-term shot-to-shot pulse energy stability. Flashlamp-pump systems as specifically excluded because of their poor shot-to-shot noise and frequent maintenance.
- System is to be HALT/HASS Certified for maximum robustness, relialbity, and day-to-day performance.

Specifications of Regenerative Amplifier with Stretcher and Compressor

Performance and Capabilities:

- Pulse Energy >4.0mJ @ 1 kHz and nominal wavelength of 800nm

Pulse Width < 100 fSec at nominal 800nm wavelength

Energy Stability < 0.5% rms over 8 hour period

Pulse Repetition Rate 1kHz, with option to upgrade to 10kHz

Spatial Mode Gaussian, TEM_{00} with $M^2 < 1.3$.

Pulse Contrast Ratio >1000:1 pre-pulse

>100:1 post-pulse

Specifications of Required Optical Parametric Amplifiers

Performance and Capabilities:

Wavelength coverage Fundamental – capable of 1140 to 2600nm with computer control tuning and wavelength selection. Fundamental design is using white light continuum generation seeding.

Ouput power – Greater than 220uJ (signal plus idler) with 1.0mJ input @ nominal 130fs. Energy scale is linear to 3.5mJ input.

Design configuration – For ease of operation and enhanced eye safety, we require that

all optics for OPA operation be housed in a single enclosure.

4th Harmonic generation – FH (Signal) 285nm to 400nm with greater than 10uJ and FH (Idler) 400-480nm with greater than 10uJ per pulse with 1.0mJ input

Sum Frequency generation – SF (Signal) 470nm to 533nm with greater than 70uJ and SF (idler) 533nm to 580nm with greater than 50uJ per pulse with 1.0mJ input

2nd Harmonic generation – SH (Signal) 580nm to 800nm with greater than 50uJ and SH (idler) 800nm to 1150nm with greater than 50uJ per pulse with 1.0mJ input

Our system schematic is shown in Fig. 1.

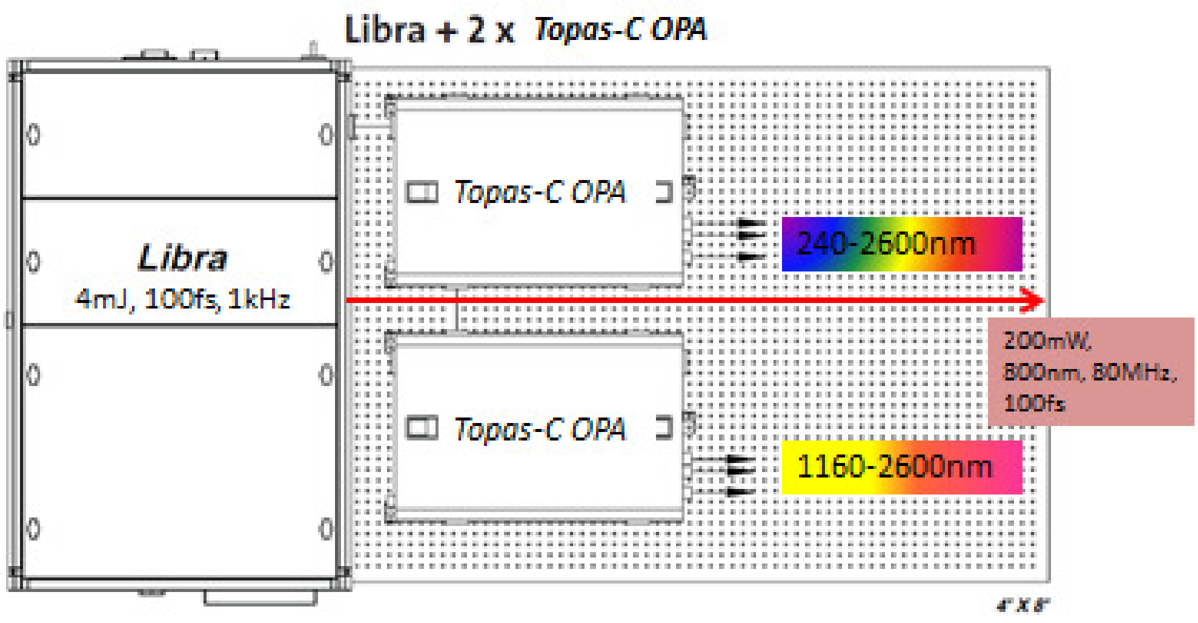

Figure 1. Schematics of our laser systems, including Libra-F-HE- Thermally Stablied Regenerative-Cavity Amplifier with Stretcher and Compressor and two TOPAS-800-FS Optical Parametric Amplifiers.

Figure 2 shows a fully-operational system installed in our laboratory.

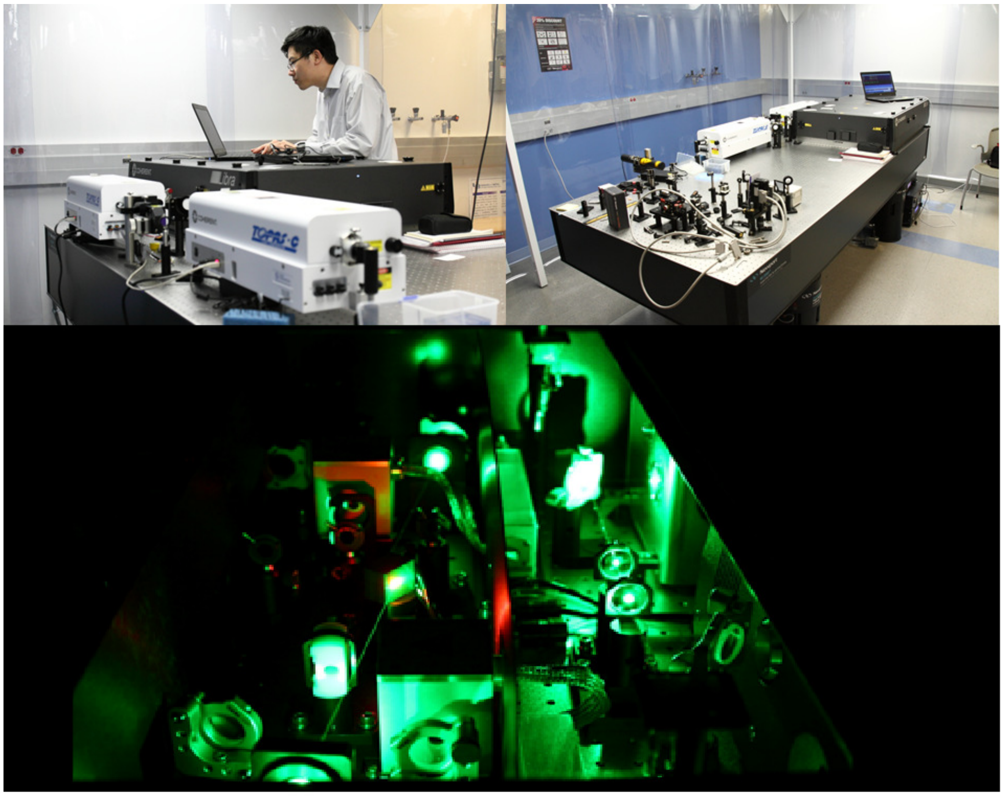

Figure 2. Femtosecond laser system installed in our laboratory.

This system is/was used in several DoD-supported studies, including current ARO-supported project “Novel Materials and Structures for Nonlinear Optics” (W911NF1510146), current ARO-supported project “Light Filamentation Science” FY 2011 Multidisciplinary University Research Initiative Program (MURI) add-on (W911NF-11-0297), completed ARO-supported project “Nonlinear Topological Surface States in Meta-Crystals” (W911NF1610270), current ARO-supported project “Parity-Time Photonic Synthetic Media: From Nonlinear and Singular Optics to Lasing” (W911NF1510152), current ONR-supported project “Nonlinear Light-Metasurface Interactions in the Mid-Infrared Range” (N000141613020), and completed DOE-funded project “Structured Light-Matter Interactions Enabled by Novel Photonic Materials” (DESC0014485).

Here, we summarize some of the results obtained using this laser system.

Nonlinear refractive index measurements using beam deflection setup

We built, tested and currently use beam deflection setup for nonlinear materials characterization. This setup benefits from low-repetition rate femtosecond system that we obtained using DURIP because it allows to measure nonlinear refractive index change due to Kerr nonlinearity, without any significant thermal component. Figure 3 shows the schematic illustration of the setup and our measurement results.

Beam-deflection technique is a simple and accurate approach to nonlinear characterization of ultra-fast nonlinearities as the measured signal is directly proportional to the induced refractive index change, yielding both the magnitude and sign of the nonlinear refraction. The excitation and probe beams are first attenuated and spatially filtered to ensure a Gaussian spatial profile. After the spatial filters set of wave plates is used to control the polarization of each beam, allowing for studies of the anisotropy of the nonlinear effects. A delay line is used to temporally delay the excitation beam.

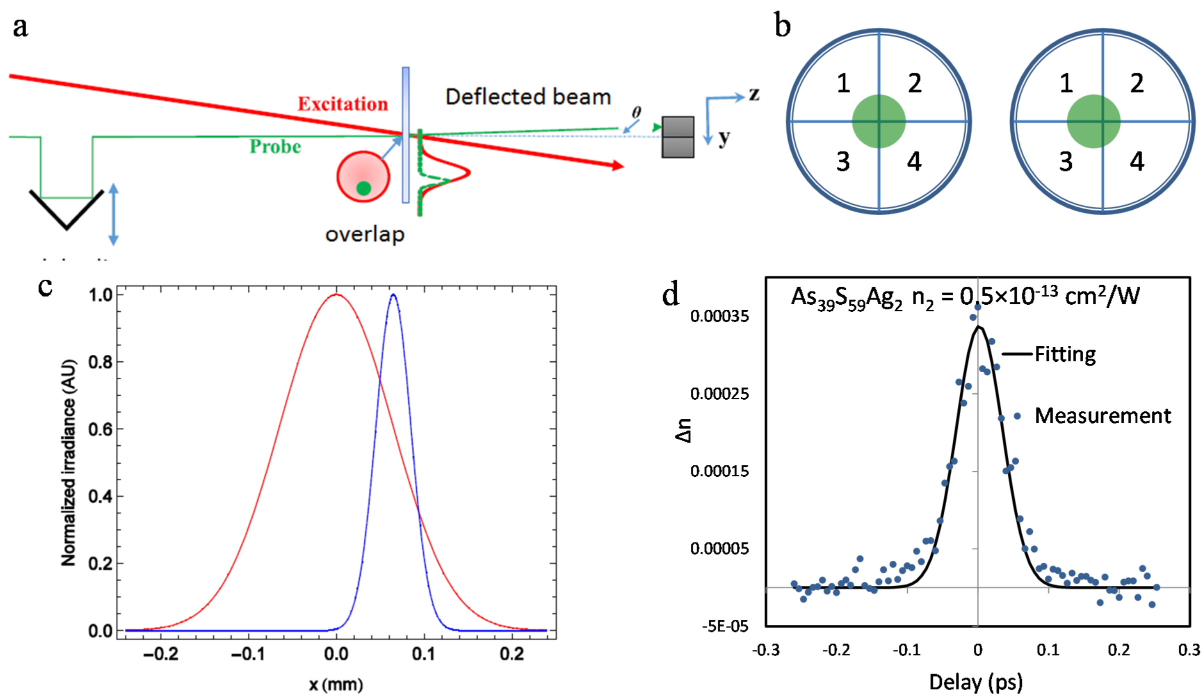

Figure 3. (a) Beam deflection schematic. (b) Quad cell detector schematic with probe beam centered on quad cell (left) and probe shifted on quad cell (right). (c) Overlap of excitation (red) and probe (blue) beam for maximum deflection. (d) An example of beam deflection measurement result for $As_{39}S_{59}Ag_2$ sample.

Both the sample and detector are mounted on 3-D stages to allow for precise translation. The deflection of the beam is measured by a quad-segmented diode. The quad-segmented diode consists of a zero-bias silicon diode operated in photoconductive mode segmented into four sections, as seen in Fig. 3(b). The segmentation of the diode allows it to measure very small beam displacements, which will prove critical to our experiments. Each section has an independent output channel which is then converted from current to voltage using four gain matched transimpedence amplifiers. The experiment was calibrated using a quartz sample.

The nonlinear response of quartz is composed primarily of the ultrafast electronic response, so

Average power (mW)	0.035	0.75	1.15
Peak intensity (GW/cm^2)	10.84	232.4	356.3

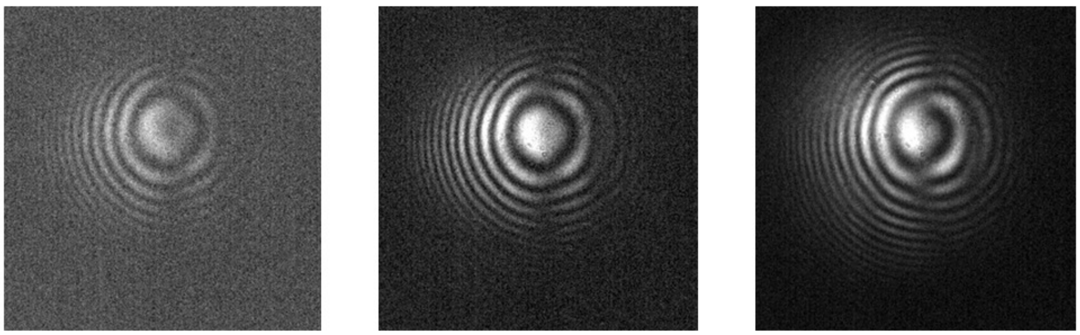

Figure 4. Interference patterns showing intensity-dependent switching between the Hermite-Gaussian beam (no spiral) and vortex beam (spiral interference pattern).

that the deflection signal follows the cross correlation of the pulses. As an example, Fig. 3(d) shows our measurements for the $As_{39}S_{59}Ag_2$ sample (Fig. 3c).

Reconfiguring structured light beams using nonlinear metasurfaces

We designed a nonlinear metasurface composed of off- and on- resonance structures. We combined these two types of structures to realize reconfigurable structured light beam that switches between the Hermit-Gaussian and vortex shape depending on its own intensity. Using our femtosecond laser system, we demonstrated this switching effect in laboratory experiment (Fig. 4).

Topological photonic crystals

In this project we designed and experimentally studied, using the femtosecond system obtained through this DURIP, topological photonic crystal that supports edge states at the interface between the trivial and topological parts of the crystal (Fig. 5). These edge states are topologically protected and robust against structural disorders and imperfections. Their propagation is supported along arbitrarily shaped paths and around defects.

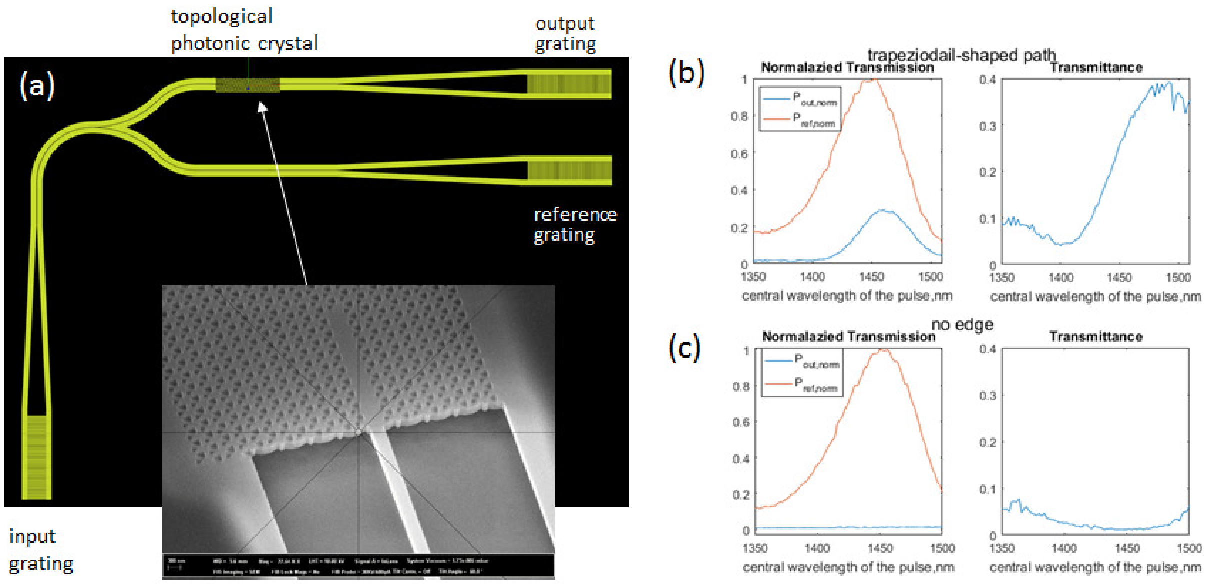

Figure 5. Topological photonic sample (a) that was characterized using the femstosecond laser system obtained with DURIP; (b) Transmission through a trapezoidal path; (c) Transmission without the edge state (no transmission).