REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY) 19-10-2015	2. REPORT TYPE Final Report	3. DATES COVERED (From - To) 25-Aug-2014 - 24-Aug-2015

4. TITLE AND SUBTITLE
Final Report: 500 GHz Optical Sampler for Advancing Nonlinear Processing with Generalized Optical Pulses

5a. CONTRACT NUMBER
W911NF-14-1-0591

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611103

6. AUTHORS
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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
Northwestern University Evanston Campus
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Evanston, IL 60201 -3149

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
65112-PH-RIP.1

12. DISTRIBUTION AVAILIBILITY STATEMENT
Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT
We received a 500 GHz optical sampler for use in our optical laboratory. It has been used in support of various tasks including generating specific pump modes for tailored up-conversion processes.

15. SUBJECT TERMS
optical sampling

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Gregory Kanter
a. REPORT UU	b. ABSTRACT UU	c. THIS PAGE UU	UU		19b. TELEPHONE NUMBER 847-467-1801

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

Report Title

Final Report: 500 GHz Optical Sampler for Advancing Nonlinear Processing with Generalized Optical Pulses

ABSTRACT

We received a 500 GHz optical sampler for use in our optical laboratory. It has been used in support of various tasks including generating specific pump modes for tailored up-conversion processes.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

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Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

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TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

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TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

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TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
gregory kanter	0.00	
FTE Equivalent:	**0.00**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

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The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

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Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

This equipment is used in support of experiments including tailored up-conversion experiments. We have found it to be superior to our FROG system and use it regularly. Small changes in the pulse profile are visible in near real-time.

Technology Transfer

Commercially available compact fiber-based mode locked lasers can have > 5 THz of coherent bandwidth, which is orders of magnitude beyond that obtainable with electronics. Wide bandwidth pulses have a variety of applications such as in microwave signal processing, ultra-wideband communications, and photonic analog-to-digital-conversion. Moreover, the high peak powers attainable in these short pulses make them well suited for nonlinear interactions. Nonlinear fiber optics is particularly useful due to the availability and huge installed infrastructure of low loss fiber optical cable.

Arbitrary optical waveform generation (OAWG) modifies the optical spectral amplitude and spectral phase of an optical signal in order to generate programmable optical pulse shapes. OAWGs have demonstrated sub-ps resolution control of optical pulses. Various techniques for measuring such complex optical pulses have been developed. The simplest and most robust technique is an optical sampling method which mimics the operation of more common electrical sampling oscilloscopes but allows for much larger bandwidths. While traditional samplers with optical interfaces are typically limited to ~50 GHz bandwidth, a commercial optical sampler sold by EXFO Inc. samples directly in the optical domain attaining an inherent bandwidth of 500 GHz thus allowing for temporal resolution of ~1 ps. Such a remarkable resolution is attainable without relying on complex reconstruction algorithms that are prone to artifacts nor does it rely on nonlinear spectral measurements that typically require high input optical powers. Moreover, the measurement time is not limited by the algorithm processing time or any mechanical tuning time and thus can produce accurate results much faster than other methods. This is particularly important when the measurement result is to be used to optimize a complex system with many adjustable parameters, such as an OAWG. Additionally, unlike coherent measurement techniques, the optical sampler has few requirements on the signal rate. For instance, the same instrument is capable of pulse rates up to 640 GHz. This makes the instrument useful for a huge class of experiments. The optical sampler usually does not even require a clock (trigger) input from the user, which is very convenient from the user perspective. Optical samplers can thus provide reliable high resolution temporal measurements of repetitive optical signals quickly and conveniently.

The Center for Photonic Communication and Computing (CPCC) at Northwestern University is a world leader in telecommunications-band quantum communications research, having developed the first fiber-based entangled photon source, the first ultra-fast low-loss single photon switch, and the first telecom-band linear optics C-Not gate. We have also developed classical technologies such as tunable fiber-based parametric oscillators, all optical clock recovery, and all optical pulse regeneration that are applicable to communications and metrology applications.

Recently our team has developed a series of technologies based on high speed temporal control of quantum optical signals. The methods manipulate optical pulses with temporal features typically on the order of 1-10 ps to control quantum nonlinear interactions including quantum frequency conversion (QFC). QFC has been used for many years to convert the wavelength of a quantum state to a different wavelength in order to better interface to single photon detectors or atomic interactions (quantum memories). Northwestern has extended the QFC concept to allow for here-to-fore impractical interactions, such as converting an arbitrary linear superposition of overlapping time-mode quantum states or efficiently frequency doubling a pulse with a bandwidth far in excess of the phase matching bandwidth. This new variant of QFC requires combining nonlinear interactions with precisely shaped optical pump pulses. It is reminiscent of optimally shaping optical pulses for coherent control of quantum mechanical processes such as ultrafast chemical reactions, a technique which has had wide implications, but in our case the pulse optimization is performed in order to tailor a nonlinear interaction to allow for previously inaccessible types of quantum measurements. When operating on

1550 nm light, the wavelength of choice for optical fibers, QFC has the additional advantage that the pump and quantum signal can both be in the 1550 nm band, which is convenient since this wavelength has copious available infrastructure. However the converted signal wavelength can be chosen for optimal detection efficiency using low cost, high efficiency Silicon single photon detectors. Over the last few years, we have built up substantial expertise for analyzing and simulating the type of multi-mode nonlinearities and quantum effects that QFC can be applied to, and we have begun a major experimental research effort to demonstrate and optimize this technology.

The CPCC has also developed all optical switches capable of controlling quantum pulses on a fast time scale with very low loss. These switches are a basic tool for manipulating quantum states and can be used for multiplexing/demultiplexing signals, generating single photon states, exceeding the classical limit on information efficiency per photon, and measuring high dimensional entanglement. The combination of high speed quantum switches and mode-selective QFC interactions can have a significant impact on quantum information science including quantum key distribution and low photon number (deep space) communications. However optimizing these types of systems generally requires precise control over optical pulses on a 1-10 ps time scale. We do have the ability to shape pulses on this time scale, for instance using a commercial “Waveshaper” from Finisar. Measuring such pulses, however, can be difficult, error prone, and time consuming.

We acquired the 500 GHz EXFO optical sampler to enhance our ability to measure short optical pulses and thus better control, simulate, and optimize the nonlinear quantum interactions of interest. Because cutting-edge experiments that manipulate quantum states usually involve combining multiple advanced technologies, it will be of great help to make the routinely required pulse measurement technique as reliable and robust as possible, thus suggesting the use of the aforementioned commercially available optical sampling equipment. The lessons learned from better quantum control can also be applied to classical experiments that utilize similar nonlinear interactions, such as optical parametric amplifiers or signal regenerators. In addition to characterizing pulses, we note that the sampler is also useful for measuring eye diagrams of very high bit rate signals, allowing us to emulate communication systems at rates which would otherwise be totally impractical to work with. This enables the university to continue to research future communication systems, and in particular the use of nonlinear signal processing to augment such systems, without requiring specialized multi-million dollar facilities.