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14. ABSTRACT

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STEM Degrees: 0 **STEM Participants:** 0

Major Goals: The detection of the individual members in a mixture of similar chemicals, biologics or materials in a host of circumstances is a widely-recognized DoD need of high importance, which has generally defied traditional means at sensing in complex scenarios. This goal is especially difficult when the sample cannot be actively manipulated or subject to chromatography techniques (e.g., the need applies to any sample which must be sensed in situ regardless of whether it's within centimeters or at meters or even further away). This multi-species detection challenge becomes increasingly demanding when the species for discrimination have broad nearly featureless spectra, which is often the case for large biological molecules, that in turn are surrounded by a complex spectrally active media as well. In recognition of this need, as background for the present research, we developed the principle referred to as optimal dynamic discrimination (ODD) based on the use of quantum control techniques which showed that the prospect existed for achieving high quality discrimination, although the necessary optical resources must be determined in the laboratory tailored to the application. Importantly, ODD relies on the detectable discriminating features being (quantum) dynamic in nature, which is very sensitive to even small molecular characteristic differences that hardly show up with ordinary spectroscopic means. Previous preliminary experiments demonstrated that ODD was a sound principle capable for laboratory implementation. But in these prior studies, we also discovered that noise in the controls, available bandwidth for pulse shaping, and high sensitivity detection are all factors that had reached their limits using standard laser resources and fluorescence-based detection for the purpose of multiplexed sensing of complex species. Thus, in the planned research, we turned to optical frequency combs (OFCs) as a means for simultaneously addressing all of these needs by exploiting the special features of the OFCs. First, frequency combs have enormous coherent bandwidth, which permits tailoring the radiation to take advantage of even the smallest of distinguishing molecular dynamical features in one specie versus another while simultaneously drawing on the noise stability of OFC's. Second, utilizing the general principles of quantum control, we know that detection will be enhanced by operating in a nonlinear fashion and this can be directly achieved by splitting the OFC beam into several separate beams which may be individually shaped and combined in the test sample for maximum detection performance. The combined beams in each sample will create unique quantum dynamics, which may then be probed in the coherent dynamical regime to create optimally distinguishing signals for heterodyne detection. Third, we aim to take advantage of the special feature of OFCs having essentially quiet background free domains lying between their myriad of comb lines. That is, the goal is to actually perform the detection at frequencies in between the background comb lines. We intend to achieve this capability by the introduction of high frequency modulation into each of the separate comb beams where the modulation is at incommensurate frequencies such that their particular combinations induced in the sample may be readily lock-in detected lying in the quiet regime between the comb lines. Finally, all of these OFC-based technological capabilities are planned to be drawn together using optimal control techniques with the aim of ultimately pushing the boundaries of multiplexed detection as far as possible in terms of the number and degree of similarity of the species for detection. The shape of the pulses for ODD discrimination needs to be optimally determined in the laboratory, and an integral part of the research is the development of suitable algorithms for this purpose. We have several prospects which will be tested in simulation and then in the laboratory ODD experiments. We aim to lay the foundation for pushing the limits of detection for practical immediate applications as well as to determine the nature of next generation technology to enhance multiplexed detection even further. We also aim to assess the ability to transfer the technology to form a robust and ideally practical instrument for laboratory and field use.

Accomplishments: See attached PDF File

Training Opportunities: The research was carried out by two postdoctoral associates and one graduate student, covering all aspects of the experimental and theoretical studies. The group works as a team, such that everyone is involved in a rotating basis in the associated activities, thereby assuring the widest experience and knowledge in each of the scientists involved. We also have close interactions with molecular biologists at Princeton directly interested in advanced deduction capabilities.

Results Dissemination: As the research is in midstream for its multiplexed detection goals, we have held off preparation of a manuscript even on the experimental design. However, we published a paper that has drawn considerable attention in the scientific press, concerning what might be called anti-discrimination (How to Make Distinct Dynamical Systems Appear Spectrally Identical, A. Campos, D. Bondar, R. Cabrera, and H. Rabitz, Phys. Rev. Lett., 118, 083201, 2017). This paper has shown that it is, in principle, possible to find distinct pulse shapes that can produce the same dipolar emission from virtually any substance, whether described classically, quantum mechanically, open, or closed to its environment. This rather startlingly result indicates that in the case of dipolar emission, knowledge of the outcome signal alone would not be able to determine the actual substance in the sample. Achieving this result utilized special mathematical tracking control techniques along with the special nature of dipolar emission. Although the result is surprising, it in no way obviates the principle behind the ODD nonlinear signal detection employed in the OFC experiments in the present research. This paper gives fundamental insights into multi-species control under certain limited detection regimes, and it especially indicates that operating nonlinearly is crucial for multiplex performance of optimal dynamic discrimination. Most importantly, the new OFC discrimination laboratory design and its experimental proof of principle capabilities is being prepared for publication.

Honors and Awards: The PI received an Alexander von Humboldt award for his laser control research.

Protocol Activity Status:

Technology Transfer: A provisional patent application for novel optical pulse compression apparatus was filed.

PARTICIPANTS:

Participant Type: PD/PI
Participant: Herschel Rabitz
Person Months Worked: 2.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

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Participant: Alexei Goun
Person Months Worked: 15.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
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Project Contribution:
International Collaboration:
International Travel:
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Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Ayan Chattopadhyay
Person Months Worked: 4.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Optimal Dynamic Discrimination of Similar Molecules Exploiting OFC Sources

Contract# W911NF-16-0062

Final Report Period: August 1, 2016 to February 15, 2018

Distribution Statement

Approved for public release

Major Goals

The detection of the individual members in a mixture of similar chemicals, biologics or materials in a host of circumstances is a widely-recognized DoD need of high importance, which has generally defied traditional means at sensing in complex scenarios. This goal is especially difficult when the sample cannot be actively manipulated or subject to chromatography techniques (e.g., the need applies to any sample which must be sensed *in situ* regardless of whether it's within centimeters or at meters or even further away). This multi-species detection challenge becomes increasingly demanding when the species for discrimination have broad nearly featureless spectra, which is often the case for large biological molecules, that in turn are surrounded by a complex spectrally active media as well. In recognition of this need, as background for the present research, we developed the principle referred to as optimal dynamic discrimination (ODD) based on the use of quantum control techniques which showed that the prospect existed for achieving high quality discrimination, although the necessary optical resources must be determined in the laboratory tailored to the application. Importantly, ODD relies on the detectable discriminating features being (quantum) *dynamic* in nature, which is very sensitive to even small molecular characteristic differences that hardly show up with ordinary spectroscopic means. Previous preliminary experiments demonstrated that ODD was a sound principle capable for laboratory implementation. But in these prior studies, we also discovered that noise in the controls, available bandwidth for pulse shaping, and high sensitivity detection are all factors that had reached their limits using standard laser resources and fluorescence-based detection for the purpose of multiplexed sensing of complex species. Thus, in the planned research, we turned to optical frequency combs (OFCs) as a means for simultaneously addressing all of these needs by exploiting the special features of the OFCs. First, frequency combs have enormous coherent bandwidth, which permits tailoring the radiation to take advantage of even the smallest of distinguishing molecular dynamical features in one specie versus another while simultaneously drawing on the noise stability of OFC's. Second, utilizing the general principles of quantum control, we know that detection will be enhanced by operating in a nonlinear fashion and this can be directly achieved by splitting the OFC beam into several separate beams which may be individually shaped and combined in the test sample for maximum detection performance. The combined beams in each sample will create unique quantum dynamics, which may then be probed in the coherent dynamical regime to create optimally distinguishing signals for heterodyne detection. Third, we aim to take advantage of the special feature of OFCs having essentially quiet background free domains lying between their myriad of comb lines. That is, the goal is to actually perform the detection at frequencies in between the background comb lines. We intend to achieve this capability by the introduction of high frequency modulation into each of the separate comb beams where the modulation is at incommensurate frequencies such that their particular combinations induced in the sample may be readily lock-in detected lying in the quiet regime between the comb lines. Finally, all of these OFC-based technological capabilities are planned to be drawn together using optimal control techniques with the aim of ultimately pushing the boundaries of multiplexed detection as far as possible in terms of the number and degree of similarity of the species for detection. The shape of the pulses for ODD discrimination needs to be optimally determined in the laboratory, and an integral part of the research is the development of suitable algorithms for this purpose. We have several prospects which will be tested in simulation and then in the laboratory ODD experiments. We aim to lay the foundation for pushing the limits of detection for practical immediate applications as well as to determine the nature of next generation technology to enhance multiplexed detection even further. We also aim to assess the ability to transfer the technology to form a robust and ideally practical instrument for laboratory and field use.

Accomplished under the Goals.

The DARPA project was very successful and the Milestones are listed below. A summary of the detailed achievements is given after that.

<u>Statement of Work</u>

Phase 1

Task 1: (Year 1) OFC based ODD for multi-species sensing. The contractor shall obtain a commercial OFC source and construct the experimental setup to quantitatively characterize mixtures of spectrally overlapping bio-chromophores using the shaped comb source.

1.1 Obtain the frequency comb, test its operation.

1.2 Construction of the optical pulse shaper for the pump, probe and heterodyne beams.
Milestone: Demonstrate frequency locking of probe and heterodyne beams; demonstrate creation of a transform limited pump beam.

1.3 Quantification of the sensitivity in the optimized linear measurement; determination of the composition of the mixture of two chromophores (Tag RFP and Turbo FP650) (Stage 1).
Milestone: Detection and quantitative concentration measurement of two spectrally overlapping species (Tag RFP and Turbo FP650) in the linear spectroscopic regime; establish the baseline performance

1.4 Construction of the high frequency modulation pump - lock in amplified, and heterodyne-probe system
Milestone: Measurement of the spectrally resolved, heterodyne detected pump-probe signal (Tag RFP).

1.5 Creation of the computational model of non-linear susceptibilities.
Milestone: Third order non-linear susceptibilities for model systems

1.6 Computational model of composition uncertainties for each Stage of the measurements.
Milestone: Estimates of standard deviations in composition for each model of the measurements in Stages 1, 2 and 3.

Task 2: (Year 2) We will evaluate the performance of adaptive optimization for composition detection, develop optimal algorithmic tools for signal analysis to extract the chemical composition from the ODD-OFC signals. The set of the optical tags will be expanded.

2.1. Create advanced data analysis algorithms for deconvolution of the signals from multiple species. Comparison of least squares, Bayesian and D-MORPH regression approaches for composition determination with large-scale data analysis.
Milestone: Evaluation of performance of data analysis algorithms for the composition detection of a mixture of three proteins (Tag RFP, Turbo FP650, Turbo FP602)

2.2. Adaptive optimization of the pump and probe pulse shapes in the composition detection experiment (Stage 2).
Milestone: Library of the optimal pulse shapes for the detection of a mixture consisting of three chromophores (Tag RFP, Turbo FP650, Turbo FP602). Comparison of the performance of adaptively optimized pulse set with a random pulse set and Stage 1 detection

2.3. Adaptive optimization of the pump, probe and heterodyne pulse shapes in the composition detection experiment (Stage 3).
Milestone: Library of the optimal pulse shapes for the detection of a mixture consisting of three chromophores (Tag RFP, Turbo FP650, Turbo FP602). Comparison of the performance of adaptively optimized pulse set with a random pulse set and detection in Stages 1 and 2.

2.4 Identification of fundamental limits to detection: requirements for the next generation of sources, modulators, detectors.
Milestones: Scaling relations for the composition uncertainties, number of species that may be discriminated as a function of noise and power characteristics of future sources.

Please note that upon discussion of the overall project with Prem at the Denver DARPA program review, he agreed that we could skip the linear detection step 2.1 and go directly to the prime goals of the project for developing the nonlinear detection capability in Milestones 2.2-2.4

A. Experimental Optimal Dynamic Discrimination and Composition Measurements utilizing an Optical Frequency Comb (OFC).

We have constructed the experimental apparatus that utilizes an OFC as an optical resource, combined with pulse shaping and electro-optic modulation. The apparatus detects the sample signal through lock-in amplification, importantly with the signal lying in the low noise domain between the comb lines. A general schematic of the apparatus is in Figure 1. After the OFC source, the beam goes through an optical compressor that compensates for the large amount of dispersion accumulated in the electro-optic modulators that follow. Then the beam is split into 4 separate components. Three of the beams serve as the controls that are shaped and modulated at 23, 17 and 20MHz for subsequent lock in detection. The four beams are sent though the liquid crystal-based optical pulse shaper. The large aperture of the pulse shaper allows us to multiplex all operations of the four beams in the same optical pulse shaper. Propagation of optical beams through the same pulse shaper in close vicinity to one another permits reducing the influence of temperature fluctuations from air currents, thus improving the beam's stability and subsequent accuracy of the measurements.

Together, the three control beams create a non-linear polarization in the sample. The nonlinear polarization is created at 23-17+20=26MHz; note that other complimentary frequency modulated signals were also created, but they were not utilized in the present proof of principle experiments. The fourth shaped beam enables heterodyne detection. The 26MHz signal is detected utilizing the lock in amplifier. The spectral content of a typical signal is illustrated on Figure 2. The clear distinction of the frequency of the non-linear polarization from the control beam's frequencies allows for a convenient detection of the sample's signal. Furthermore, the high frequency modulation enabled recording of the sample signal in the nearly optical noise free background between the comb lines to obtain a high S/N level. We remark that the apparatus is the first time that an OFC has been used as a source in such a control-detection scenario based on quantum control ODD principles. Also, there were many technical hurdles that were overcome, which are not explicitly indicated in the schematic of Figure 1.

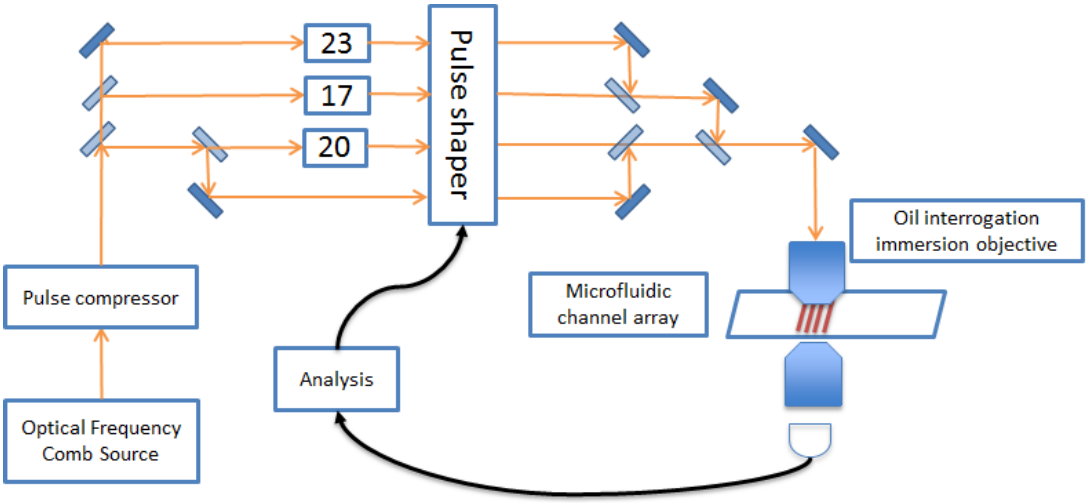
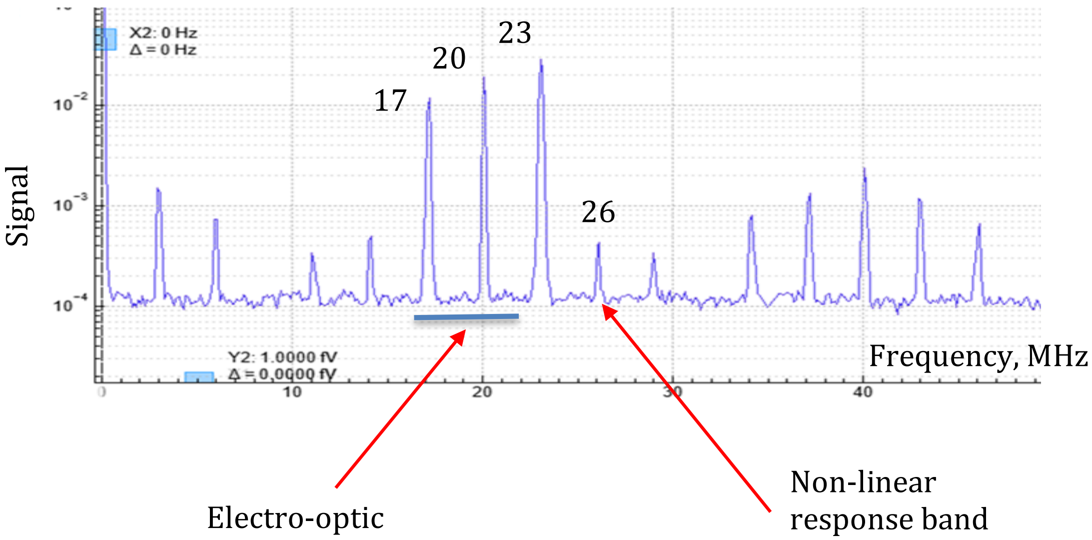


Figure 1. The overall schematic of the experimental apparatus.



Electro-optic modulation bands

Non-linear response band 26=23-17+20

Figure 2. Spectrum of the detected signal. Importantly, (a) the modulated signal at 26MHz lies in the near noise free space between the comb lines and (b) the signal can be detected by lock in. The other spectral features either correspond the to comb lines or complimentary modulation signals that were not used in the experiment, but they can be used in the further development of the measurement system for scaling to lager numbers of chromophores with enhanced signal sensitivity (see Section **B.**)

As a biological chromophore system for a proof of principle test of the detection concept we chose protein-based light harvesting complexes(LHC). These complexes possess high absorption cross sections with spectra, conveniently located in 700-900nm region, and they can be created in very simple biological environments such as a bacterial host. Thus, light harvesting complexes represent a convenient platform for observation of complex biological circuits, although such applications were not the goal of the key proof of principle detection demonstrations in the present DARPA program.

A system of three biological LHC chromophores were chosen as samples for the discrimination experiments: *Rhodopseudomonas acidophila* (Chromophore 1), *Chromatium purpuratum* (Chromophore 2). *Rhodobacter sphaeroides* (Chromophore 3). The strongly overlapping absorption spectra of these chromophores are shown on Figure 3. The concentrations of pure samples were: Sample 1 (LHC *Rhodopseudomonas acidophila*) 1.2μM, Sample 2 (*Rhodobacter sphaeroides*) 0.4μM, Sample 3 (LHC *Chromatium purpuratum*) 0.6μM. The experiment first worked with the pure samples to learn how to shape the OFC three control beams to discriminate the species.

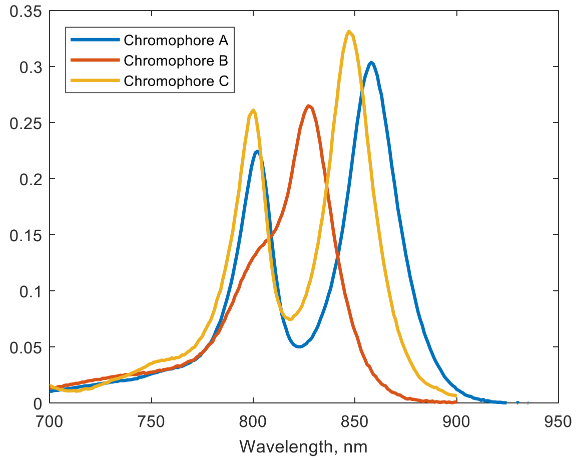


Figure 3. The strongly overlapping absorption spectra of the three light-harvesting complex (LHC) chromophores used as a test family of molecules for OFC-based optimal discrimination.

We have performed learning control experiments in order to determine the optimal set of the laser pulses that can discriminate between the three chromophores. In order to perform the final discrimination between the three chromophores, (i.e., and determine the composition of a mixture of these chromophores) we need to solve a system of linear equations. One of the most important factors determining the accuracy of the mixture concentrations is the value of the determinant of the matrix of coefficients in the system of equations. The determinant is measured using the set of pure chromophores and its value is optimized by utilizing the library of the most discriminating pulses. A typical distribution of determinant values created throughout the pulse combination library is illustrated on the Figure 4.

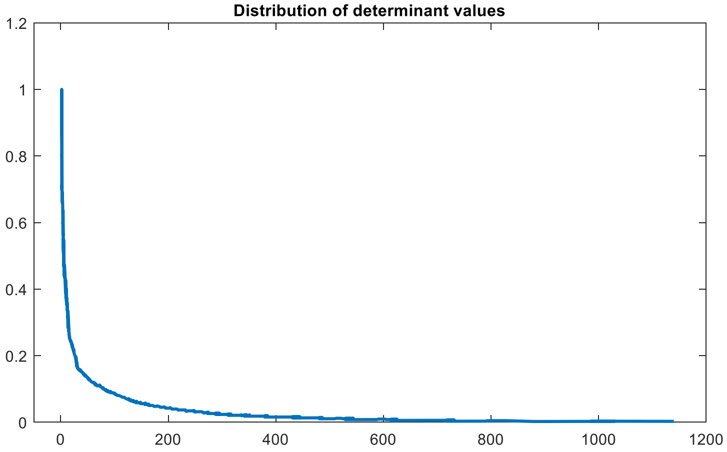


Figure 4. Typical distribution of determinant values in the library of pulse shapes.

Once the library of discriminating pulse shapes was determined we performed the protein mixture detection experiments. Naturally these experiments drew on the largest discovered system determinant corresponding the highest condition number of the coefficient matrix to assure stable mixture detection. Furthermore, as will be shown below, the high quality of control and detection permitted by the comb source resulted in effectively orthogonal signals (i.e., a particular pulse would "light up" a single protein and essentially null out the signal from the others by destructive quantum interference by tailoring the control pulse shapes using the principles of ODD. This result is dramatic, considering the high spectral overlap of the proteins shown in Figure 3.

a. Measurement of pure samples as references.

First, the performance of the detection apparatus was validated on pure samples and to extract an optimal coefficient matrix for the subsequent mixture detection experiments. In the absence of noise and spectral cross-talk between the proteins, we expect that measurement of pure sample composition will result in a unit coefficient matrix (i.e., the detection is fully orthogonal for each species), as indicated in the matrix lying in the table right below.

Pure sample 1	1.0	0.0	0.0
Pure sample 2	0.0	1.0	0.0
Pure sample 3	0.0	0.0	1.0

The actual experimentally measured composition of pure samples is shown in the table below. Although the matrix is strictly not of unit form, it is clearly well conditioned, thereby providing the required stability for the subsequent mixture component experiments to follow.

Pure sample 1	1.017	0.004	0.022
Pure sample 2	0.00	1.018	0.040
Pure sample 3	0.031	0.039	1.074

In summary, the results confirm the ability to reach a very high degree of effective chromophore signal orthogonality. Note that the small discrepancy present in the coefficient matrix does not influence final mixture assessment, as the actual coefficient matrix is utilized. Importantly, by mere inspection the coefficient matrix is full rank enabling subsequent good quality detection of mixtures of the three protein chromophores.

b. Measurement of mixture composition.

As proof of principle test cases, we measured the composition of two separate mixture samples with the results shown in the two tables below. The concentrations are presented in μM/liter units; interestingly, the small focal volume of the focused laser beams implies that the actual detection sample contains a very modest number of proteins showing the high sensitivity of the method, which is very significant for future biological applications or other regimes of operation where trace detection is essential.

The measured composition of two mixture samples as a proof of concept.

The true composition, μM	0.0	0.12	0.42
Measured composition, μM	0.060/+-0.032	0.092/+-0.003	0.42/+-0.005

The true composition, μM	0.19	0.2	0.21
Measured composition, μM	0.13/+-0.03	0.20/+-0.013	0.25/+-0.003

The error estimation results are from statistical sampling. The quality of the detection results is excellent, and they provide the foundation for follow on work to establish the limit of the technique to detect a high number of complex, spectrally overlapping species in the same sample. The theoretical foundations for such scaling was examined, as described below.

B. Theoretical modeling and assessment of multi-species scaling for OFC-based detection of complex spectrally overlapping large molecules.

The goal of the theoretical analysis is to (i) assess of the feasibility to scale our OFC-based detection method to discriminate many proteins simultaneously, (ii) provide a physical basis to understand the detection principles and (iii) create estimates of the optimal control pulses to aid the subsequent learning control experiments. In order to meet these goals, we have developed a numerically efficient means for simulating the third order non-linear response of a molecular sample interacting with an OFC source. Our approach allows us to exploit the capability of OFC sources to provide high spectral resolution and broad wavelength coverage. The numerical simulations fully confirm the ability to readily place the non-linear response in between the comb lines of the laser, providing the desired background free detection capability. The species-specific nature (i.e., the orthogonality) of the non-linear response signal is controlled by shaping of the control beams; the location of each species-specific orthogonal signal is determined by the phase modulation frequencies.

The efficiency in the composition detection in the proof of principle experiments was dramatic and far better than traditional recording of incoherent fluorescence signals. Furthermore, it is highly advantageous to get away from utilizing fluorescence, as the excited electronic state is damaging to cells. We refer to this new generation of comb-ODD-based detection of chromophores as favorably operating in the so-called "zero quantum yield" regime. The theoretical and numerical analysis is fully supports this new capability developed in the DARPA program with expected favorable scaling to larger numbers of chromophores (see the discussion below).

The overall capability of the apparatus is very attractive for scaling the discrimination procedure to larger numbers of molecules with strongly overlapping spectra (e.g., proteins). The detected lock-in signal is the contraction of two tensors, one is determined by the nonlinear response of each chromophore and the other is determined by the combination of control and heterodyne beams (i.e., the entities that we can control). Even though the precise behavior of these multidimensional tensors is quite complex, importantly the lock in amplifier signal is linear in each of the control fields and in the heterodyne field. This feature makes it possible to utilize matrix decomposition methods (i.e., specifically the QR decomposition to *in silico* search for controls giving orthogonal signals amongst the multiple chromophores). Besides establishing the key scientific principle behind the ODD-based detection technique, the *in silico* design of the most discriminating pulses should provide a basis to accelerate the efficiency of the experimental learning control procedure in the laboratory. An example of such discriminating pulse designs is shown on Figure 5. As remarked in the figure caption, the apparatus readily permits utilizing orthogonal signals from many chromophores simultaneously present in a sample. We note that the favorable orthogonal detection capability of the detection depends on several factors, including (i) the utilization of background free detection of the non-linear optical response, (ii) the high S/N ratio, and (iii) the appropriate spectral resolution of pulse shaping system. We can also take advantage of using the natural presence of multiple complimentary high frequency modulation signals mentioned in Figure 2 to reduce of overall noise. Future tests of the chromophore scaling limits of the apparatus will also aim to assess the sources of noise to either reduce or eliminate them.

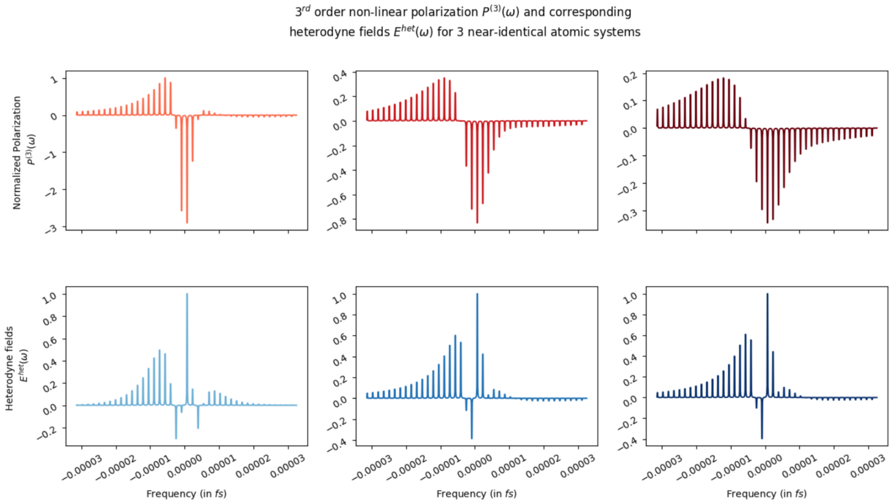


Figure 5. Orthogonalization of the non-linear optical response of three spectrally similar molecules. Note that the similar signals in the last two chromophores does not hinder their detection capability, as the distinct control pules involved make their signatures orthogonal (i.e., only one signal will show up for each specie, and this capability scales well to high numbers of species present using the comb-based quantum control principles with shaped pulses.

The easy generation of systematic very distinct optical pulses and resulting signals suggests that we should be able to reach very favorable scaling of our OFC-ODD-based detection approach. Based on the principles of quantum control underlying the technique, we have come to the conclusion that under ideal conditions the number of chromophores amenable to discrimination should be equal to the number of independent control parameters in the OFC-optical chromophore detection system. The only critical factor is that the system coefficient matrix has a good condition number, as demonstrated the proof of principle experiments; that is, full species orthogonality is not needed for practical purposes. We estimate that the number of simultaneously discriminable species could approach ~10, or possibly more, with a simple extension of the present setup. We emphasize that even reaching a capability ~10 spectrally similar species for simultaneous detection would be unprecedented and of very high value in systems biology for the real-time monitoring of biochemical pathway activity. Thus, the conservative scaling to ~10 chromophores should enable a technology transfer of our apparatus to form a commercial instrument of wide use in the systems biology community. Commercial interest has already been shown in making this transition.

Importantly the new experimental capability demonstrated in the DARPA project utilizing quantum control principles combined with comb characteristics opens up other high value applications besides detection. In particular, such additional experimental modalities include: a) measurement of the state of optogenetic switches with a minimal disturbance of their internal state b) interferometric measurement of continuous parameters such as membrane potentials or mechanical stresses within living cells, c) and the full integrated operation of multiple optogenetic switches and biological chromophores. Achieving item c) could open up an entire new era in systems biology for either understanding the origin of disease states or controlling the behavior/performance of bio-networks.

Honors and Awards

The PI received an Alexander von Humboldt award for his laser control research.

Training Opportunities

A description of opportunities for training during reporting period

The research was carried out by two postdoctoral associates and one graduate student, covering all aspects of the experimental and theoretical studies. The group works as a team, such that everyone is involved in a rotating basis in the associated activities, thereby assuring the widest experience and knowledge in each of the scientists involved. We also have close interactions with molecular biologists at Princeton directly interested in advanced deduction capabilities.

Results Dissemination

A description of dissemination during the reporting period

As the research is in midstream for its multiplexed detection goals, we have held off preparation of a manuscript even on the experimental design. However, we published a paper that has drawn considerable attention in the scientific press, concerning what might be called anti-discrimination (How to Make Distinct Dynamical Systems Appear Spectrally Identical, A. Campos, D. Bondar, R. Cabrera, and H. Rabitz, Phys. Rev. Lett., **118**, 083201, 2017). This paper has shown that it is, in principle, possible to find distinct pulse shapes that can produce the same *dipolar* emission from virtually any substance, whether described classically, quantum mechanically, open, or closed to its environment. This rather startlingly result indicates that in the case of dipolar emission, knowledge of the outcome signal alone would not be able to determine the actual substance in the sample. Achieving this result utilized special mathematical tracking control techniques along with the special nature of dipolar emission. Although the result is surprising, it in no way obviates the principle behind the ODD nonlinear signal detection employed in the OFC experiments in the present research. This paper gives fundamental insights into multi-species control under certain limited detection regimes, and it especially indicates that operating nonlinearly is crucial for multiplex performance of optimal dynamic discrimination. Most importantly, the new OFC discrimination laboratory design and its experimental proof of principle capabilities is being prepared for publication.

Technology Transfer

Technology Transfer during the reporting period

A provisional patent application for novel optical pulse compression apparatus was filed.

Participants

Prof. Herschel Rabitz 2 months
Dr. Alexei Goun 18 months
Dr. Jinhai Chen, 3 months
Mr. Ayan Chattopadhyay (graduate student) 4 months