

From “Can you phase-shift this?” to “How do you measure that?”

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ABSTRACT

This paper is an overview of my career and insights I have gained along the way. I grew up around optics in Corning, NY, got degrees in optics from University of Rochester and University of Arizona, and have been working on a large variety of projects ever since. I will cover projects that include: the development of "Digital Speckle Pattern Interferometry" and "Two-wavelength phase-shifting interferometry," teaching optical sciences courses, working on the LIGO Interferometer project, imaging biofields and biophotons, measuring effects of musical sound, imaging biological cell cultures and small critters using dynamic quantitative phase imaging, and helping clients image, measure, build and test a variety of optical systems.

Keywords: optical metrology, optical testing, interferometry, interferogram analysis, phase measurement, quantitative phase imaging, optical design, bioimaging

1. STARTING OUT

It seems like optics has been a part of my entire life. I moved to Corning, NY when I was 5 and grew up in this city that is home to the Corning Glass Works (now Corning, Inc.). My father worked there for several years on product development and marketing. My neighbor was a tool maker in the research department who worked on things like developing glass lens molding techniques. My friends' parents had many different roles working for various divisions of Corning. Every year we'd go on school field trips to the Corning museum. I don't know how many times I saw the movie about the making of the Palomar telescope blank (see Fig. 1).[1] In the community, I met and hung out with people who were pioneers and giants in optics. But, when I was a kid, these were just regular people to me. It wasn't until I became an optics major at the University of Rochester (UR), which is 100 miles north of Corning, that I began to understand who these people were in the world, and that I grew up in the midst of a very special city.

At the UR, I didn't start out as an optics major. I started out in physics and astronomy wanting to double major in music at UR's Eastman School of Music. It became obvious pretty quickly that trying to double major in music wasn't going to work when I would have to take buses back and forth across town between the main UR and Eastman campuses. Instead, I did as much music as they let me get away with. I landed in optics because a friend in marching band said I should check it out when I mentioned that it's too bad you can't see the sky in Rochester. By early in my sophomore year I decided it'd be way more fun to design and build telescopes than try to look through them in cloudy Rochester.

Highlights of my time at UR include taking multiple classes from Rudolph Kingslake. His classes covered a lot of material and were really hard. When I took his two lens design classes, my roommate and I found as many old exams as we could going back 20 or 30 years. We worked through every problem we could find. I really enjoyed

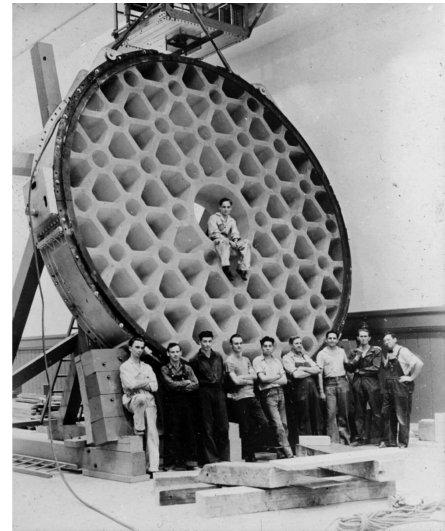


Fig. 1. Palomar Hale telescope primary blank poured by Corning Glass Works in 1934. The original blank that cracked during curing is still on display at the Corning Museum.[1]

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learning this stuff. Kingslake wouldn't allow us to use existing software packages for lens design. If we wanted to use a computer to do ray tracing, we had to write our own code. Because I had spent my previous summer writing a non-sequential ray trace in Fortran for a summer job, I put some code together using Fortran on punch cards on the UR mainframe to do ray tracing so I could design my Cooke triplet.

After receiving a BS and MS in optics from University of Rochester, I began looking for jobs. It was during a recession right after Reagan became president, so there were few companies hiring at the time. At the same time, I applied for a Howard Hughes Doctoral Fellowship from the Hughes Medical Foundation. This offered a full-ride for 3-4 years to complete a doctoral degree after a masters degree. When I was awarded this Fellowship, I jumped on this opportunity. It enabled me to choose where I wanted to go study, and I chose the Optical Sciences Center (OSC - now the Wyant College of Optical Sciences) at The University of Arizona in Tucson, Arizona. At the time it was the only other school other than the UR that had a PhD program in optics. All I knew was I wanted to do something related to speckle and interference or optical design.

Once at OSC, my Hughes Aircraft Corp. mentor wanted me to learn all I could about atmospheric propagation and statistical optics for Star Wars applications. But I found I was more interested in interferometry. After a semester at OSC I asked Jim Wyant who was also a UR graduate if I could work in his lab.[2] When he was off on sabbatical at UR he decided I was ok after asking Rudy Kingslake whether I was a good student.

The nice thing about being a Hughes Fellow was that I could choose what I wanted to do research on. My stipend was paid, and I didn't have to work on a specific research grant. When I began looking for research projects, Wyant handed me a piece of lined yellow paper that had 30 different possible research topics hand written on it. I spent the rest of the time he was on sabbatical investigating the things that sounded interesting to me on this list. Then I spent the next year after that going down a lot of blind alleys looking for something that I could do in a reasonable amount of time that piqued my interests. While doing this I learned all I could about phase shifting and phase measuring interferometry that was being done in Wyant's lab and at OSC. None of this had really been written down yet in a way you could read it and study it easily.

Near the beginning of my 3rd year in my PhD program, Wyant dropped a book chapter manuscript on my desk for review with a note attached reading "Can You Phase Shift This?" It was by Løkberg and Slettemoen on Electronic Speckle Pattern Interferometry (ESPI) which uses electrical circuitry to analyse speckle interference fringes in real time.[3] I read it, and said, yes, I can. And off I went on a journey that I had never anticipated.



Fig. 2. Kathy Creath at 1985 OSA Meeting in San Diego with demonstration poster for DSPI - digital speckle pattern interferometry (now known as digital holography).

2. PHASE MEASUREMENT INTERFEROMETRY (PMI)

To help me understand ESPI better, Gudmund Slettemoen (one of the book chapter's authors) came from Norway University of Science and Technology (aka NTNU) for a few weeks to work on a project at OSC and to teach me about ESPI. He was an invaluable mentor on this project. I designed an inline optical system similar to ESPI using an optical fiber as a colinear reference beam and wrote the software to do the phase-shifting by using a PZT actuated mirror and then analyze the data (Fig. 3).

Wyant's lab in OSC 101 was many stories underground with no windows. I often worked in the dark because someone wanted the lights off. That's how I learned to type. Despite being that far underground with all the environmental precautions made when the building was built to get good interferometric data, the motion of the elevator, as well as trucks driving along University Blvd., could be measured in my data. I often came in at 2 am when the elevator wasn't running to get my best measurements.

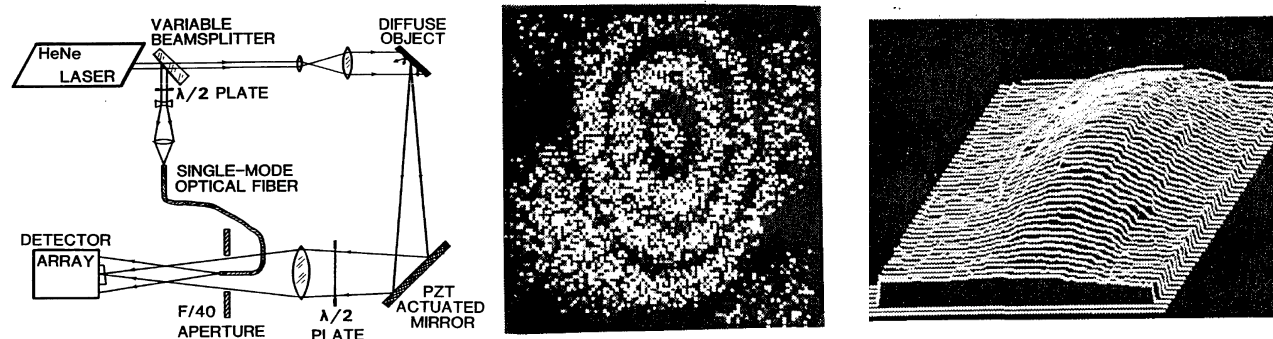


Fig. 3. (left) Digital speckle-pattern interferometry inline holography setup. (middle) DSPI fringes showing debonded area in a honeycomb structure bonded to the back of a flat plate. (right) Displacement contour map.

Developing “Digital Speckle-Pattern Interferometry” (DSPI) as a quantitative means to do everything that ESPI did was my PhD dissertation (1985).[4, 5] This also has been called “Phase-Shifting Speckle Interferometry” (PSSI) and is now more commonly known as “Digital Holography” (DH) for measurement of deformation, vibration and shape (see Fig. 2 and Fig. 3).[5] When I was doing my dissertation, the camera resolution wasn’t high enough to be able to do off-axis (Leith and Upatnieks[6]) holography so my first system created in-line Gabor holograms. The Applied Optics article I wrote on my dissertation research was one of the 50 most cited papers in the first 50 years of Applied Optics with more than 1100 citations according to Google Scholar as well as an Applied Optics editor’s top pick in non-destructive testing.[5, 7, 8]

This research utilized a digital photo-diode camera with a 100x100 pixels. Even though it was a very expensive state-of-the-art camera at the time, it required a handmade interface box made at OSC to get data into the computer. There really weren’t enough pixels to get good images with decent resolution, but this proof of concept showed the possibilities of what it could do. Even though it was very novel at the time, the University didn’t want to pursue a patent. Within 10 years you could easily purchase a megapixel camera that interfaced into a PC for much less money. This and other newer electronics technology enabled at least a handful of companies to sell instruments based upon what I had done.

While working on my dissertation, Wyant asked me if I could phase shift two-wavelengths to do synthetic-wave interferometry to extend the techniques he had developed earlier in his career.[9] After reading his papers, I said I could and that software I had already written would do it with minor tweaks. We went down to the lab, I took my camera and computer over to another experimental interferometer setup in the lab that had an argon-ion laser so that we could change wavelengths, and in a few minutes we had a two-wavelength phase-shifting measurement result. Two-wavelength phase measurement techniques for shape measurement were also introduced in my dissertation as it applied to DSPI.[10] We got a patent for this two-wavelength phase measurement technique and its extensions to multiple wavelengths when I was working at WYKO Corporation in Tucson, AZ which was co-founded by Jim Wyant (see Fig. 4).[11]

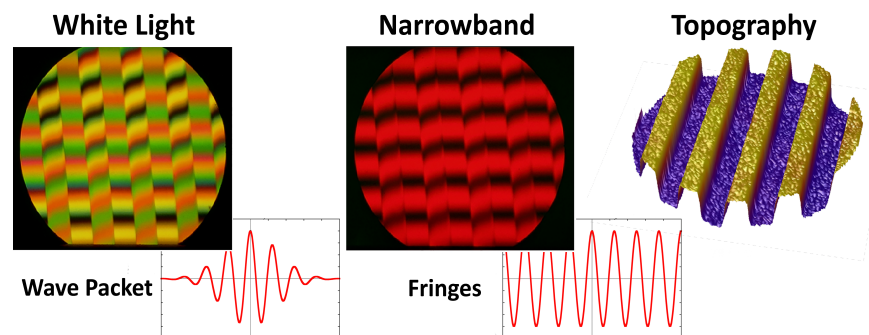


Fig. 4. Interference microscope measurement of a diffraction grating with deep topography. (left) White light interference fringes before filter inserted showing multiple fringes of depth. (middle) Fringes after red narrowband filter inserted. (right) Measurement result using two-wavelength interferometry.

3. PHASE-SHIFTING EVERYTHING



Fig. 5. Early WYKO product line based upon HP Workstations: (left) Topo, (middle) Sirius, and (right) Ladite.

measurement interferometry (PMI), helped create a very influential field of optics, and developed instruments every lab and shop could own. It was one of the most creative phases of my life.

While at WYKO I wrote a lot of papers. One was a monograph titled “Phase Measuring Interferometry” (PMI) that was published in “Progress in Optics, Vol XVI” edited by Emil Wolf from University of Rochester. [12, 13] I wrote this monograph because there was hardly anything written down about PMI, and it was becoming an important enabling technology. I had spent a lot of time figuring out the little intricacies and necessities to make these techniques work and wanted to explain how it worked so others could use it. When I sent the completed chapter to Emil Wolf, he told me he was delighted to receive a completed book chapter that required little editing. Normally, he said he had to twist a lot of arms to get people to finish them. Emil corrected every typo he could find and even made sure that all the references were correct. The monograph is by far the most cited work I have ever written having received more than 2250 citations according to Google Scholar. [12, 13]

While at WYKO, in addition to applying phase-measuring techniques to all types of interferometers, I wrote a lot of software for WYKO’s HP-based interferometers. This focused developing phase-measuring algorithms as well as the interferometric data analysis (see Fig. 6).

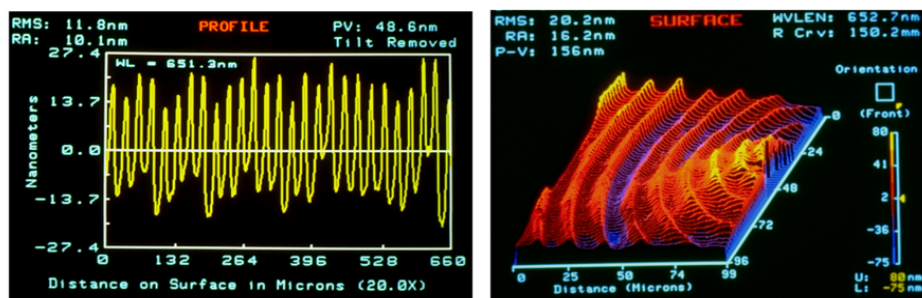


Fig. 6. Diamond turned surface: Topo 2D and Topo 3D measurements.

A key thing was making interferometer software compatible with lens design software so we could pass data back and forth. This involved a deep dive into wavefront aberration theory and Zernike polynomials. The theory and lessons learned from this contributed to another major book chapter I co-authored titled “Basic wavefront aberration theory for optical metrology” with Jim Wyant.[14] Jim had written a draft of this chapter many years earlier using the sign conventions he was familiar with at the time. I expanded the chapter, and redid all the equations and examples in right-handed coordinates to match the coordinate system of the major lens design codes and the WYKO software algorithms. This is another of my publications that has been widely cited.[15] I’ve seen bits of it crop up on websites around the world as well, and keep reminding people they need to cite the original source.

After 5 years at WYKO, I returned to OSC as an Assistant Professor in 1991. At this point, I was working on high-resolution phase-measuring interferometric microscopy through NSF SBIR grants. It utilized a Kodak mega-pixel camera that cost ~\$20K at the time. Using super-resolution combined with the techniques used to develop the WYKO TOPO microscope, the goal was to resolve linewidths down to 10nm.[16-18] The technique was very promising, but the Windows PC computer was so slow it would take overnight to analyze one measurement. The ideas and theory were well ahead of practice at that time. We demonstrated repeatable measurements with 50nm linewidth resolution, but needed more computing power to achieve our goal. In 2017 at an OSA (Optical Society of America) meeting I heard a talk by someone doing a similar thing, and they were able to do the same analysis in a minute. It took more than 25 years for the technology to catch up.

After my first semester as an Assistant Professor I had the opportunity to spend the summer at CSIRO (Australia's National Science Agency) in Sydney, NSW, Australia collaborating with P. Hariharan in the optical metrology group - a lab that was truly state-of-the-art.[19] This was the beginning of a long-term collaboration with CSIRO.

Other research from my OSC lab included a liquid-crystal, polarization PDI (point diffraction interferometer) designed and developed by Carolyn Mercer, PhD 1995, (NASA Glenn Research Center) for optical metrology of wavefronts in wind tunnels,[20] and PMI algorithm development and error analysis by Joanna Schmit, PhD 1996, (now at Onto Innovation 4D Technology).[21, 22] The Schmit-Creath algorithm is still cited in many papers, and was one of the editor's picks for the top 20 optical testing papers in the first 50 years of Applied Optics (see Fig. 7).[23, 24]

In the early 1990's at OSC I taught Optical Testing, Applied Optics, and labs for Optical Testing, Holography and Interferometry. During this time, I also served as an Applied Optics Topical Editor, and was the first woman elected to the SPIE Board of Directors (1994-1996).

4. A NEW WAVE: FROM LIGHT TO SOUND

In 1995, I was wondering what I wanted to do for the rest of my career. I had so many interests, and not enough time or energy to pursue them all. An old friend of mine whom I admired for his work-life balance asked me "are you living to work or working to live?" This conversation sent me along a new path. This launched me on the "Can you measure that?" phase of my career.

At a point in my career when most people would be specializing even more, I decided I wanted to broaden my scope and step off in a different direction. I had never lost my interest in music and it seemed to occupy all my free time. I was studying with a private teacher and practicing while playing in various semi-professional music groups around Tucson.

Ultimately, I decided to pursue music along with optics. I would use my knowledge of optics as a consultant to pay my bills and dive head first into music for a few years. I left my position at the University of Arizona and became a student again, this time in music. Over the next 7 years I earned an MM in music performance and a PhD in music with an emphasis in music theory from the University of Arizona. I never planned to become a full-time performer or teach music as an academic. I wanted to develop the other half of my brain and see how I could incorporate my scientific interests with my musical interests.

While working on my music PhD, I found myself collaborating with faculty at the Center for Integrative Medicine (CIM) while I worked on my research. I had been interested in how music affects us as human beings and our consciousness. I wanted to show that music had an effect on a biological system, but I realized from the research I studied that trying to do this with human subjects was very time consuming and very hard to control because humans have a wide range of reactions to music.

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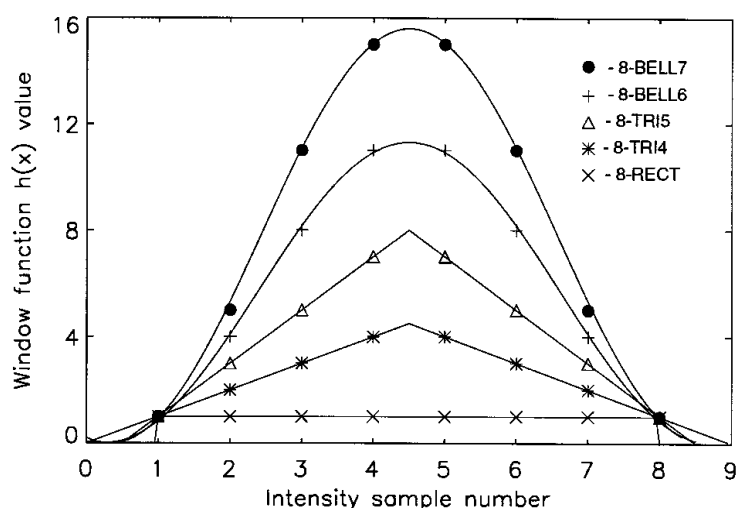


Fig. 7. (top) The beginnings of the "Schmit-Creath" algorithms. (bottom) Windowing techniques for algorithm design developed with Joanna Schmit.

What I ended up doing was using seed germination as my model biological system and measuring how fast seeds sprouted, and what percentage of seeds sprouted when exposed to silence, pink noise and musical sound. I controlled as many variables as I could and had another student count and document the results. She had no idea which set of seeds she was looking at so she would not bias the outcome. I repeated this experiment with thousands of seeds over a number of independent trials. The resulting outcome was that “musical sound” versus “no sound” (control condition) had a highly statistically significant effect, and “musical sound” versus “noise” and “no sound” as a function of time had a statistically significant effect.[25] These results were replicable over multiple independent experimental runs (see Fig. 8).

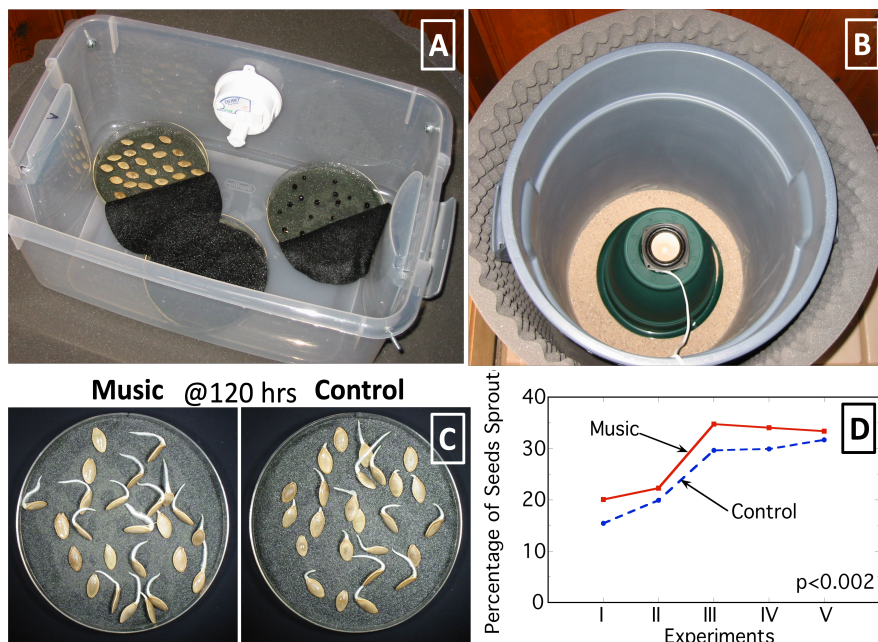


Fig. 8. (A) Seed germination set up in container measuring temperature and humidity. (B) Covered seed container is suspended above an isolated speaker in an acoustically insulated enclosure. (C) Zucchini seeds after germinating for 120 hours showing larger number sprouted with music (left) than control (right) condition. (D) Plot of results for thousands of seeds over 5 replicated independent experimental runs.

Although this was a very different type of measurement from interferometry, it was optical in that all data were captured via imagery and results were counted visually at set time increments.

5. BIOPHOTONS

After my music PhD was completed, I went back to OSC as a Research Professor. I continued my music interests outside of work, consulted, and taught Optical Fabrication and Testing to the seniors in the OSC optical engineering BS program.

I also continued collaborating with the CIM faculty developing some optical measurement techniques. We had seen research on measurement of biological changes by measuring biophotons with photomultiplier tubes.[26, 27] Biophotons are also known as “ultraweak photon emission” because sensing them is akin to counting photons. The problem was these researchers weren’t able to get imagery to pinpoint where the photons were coming from. I knew that an optics professor in the radiology department was doing time studies of fluorescence in mice using a very highly sensitive low-light imaging system in a dark chamber. I made arrangements to use the system to study biophotons. Over the next several years, I spent hours in a dark room taking long exposures of many different objects to image biophotons and see if we could document and quantify what was going on. I was able to document and quantify a number of different things I observed.[28, 29] A new kind of optical measurement.

A biophoton is simply a photon that is released during any biological process when a chemical bond is broken. Different biological processes emit these photons at different wavelengths depending upon what type of bond is being broken. This is a phenomena beyond simple blackbody radiation. When something like a plant leaf is wounded, you can see there is a lot more biophoton emission around the edges of the wound as the leaf utilizes more metabolic activity in those areas (see Fig. 9).

This work resulted in many research publications. [28, 29] Neither my co-author Gary Schwartz or myself were formally trained in biology so we did not hypothesize on exactly what biological mechanisms were taking place. But, it was obvious that simple biological systems like plant leaves or vegetables like string beans reacted to various stresses and that images of biophoton emission were a means of quantifying those reactions. I did some pilot studies using this imaging with human subjects as well, but the camera sensitivity required a roughly 15-minute exposure to get emission images from humans and most people don't want to stand still that long. Since then more sensitive cameras have been developed, but I haven't gotten back to this.

This is another of those fields of research I worked in where we showed the proof of concept, but it would take another 20 years for biologists to get serious about what mechanisms were involved. Now, the next generation of researchers are looking more deeply into connecting these effects to specific metabolic mechanisms.[30]

Back then, I kept trying to collaborate with various medical researchers on using this type of imaging in their studies, and they kept saying they could only do what was within the scope of their grant. After a few small grants for this work, I decided to move on and go back to working on optics projects that brought in more money.

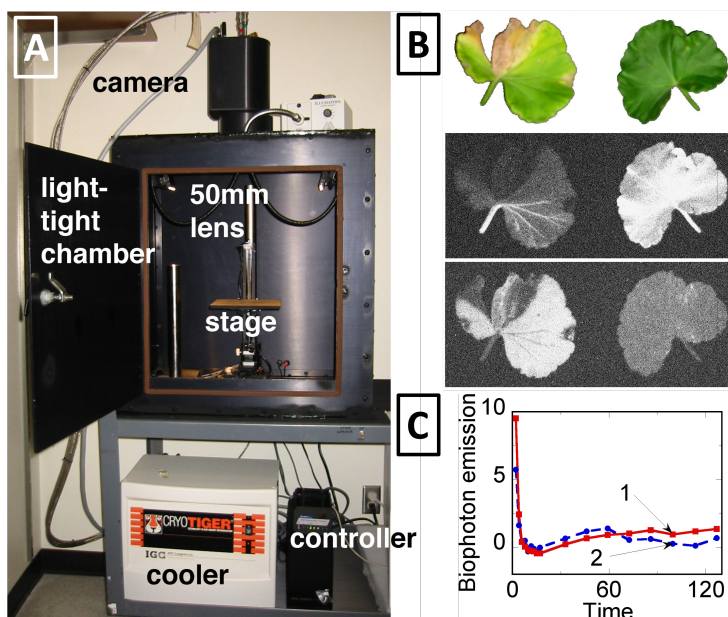


Fig. 9. (A) Light-tight imaging chamber. (B-top) Geranium leaves in different states of health. (B-middle) 1-minute exposure showing initial chlorophyll fluorescence in total darkness. (B-bottom) 10-minute exposure biophoton image after 22 minutes in total darkness. (C) Average biophoton emission for 2 areas within an injured leaf showing comparison of activity over time. The injured area (red/solid) shows more emission after a longer period of time in darkness than the healthy control area of the leaf (blue/dashed).

6. CONSULTING

Consulting seemed like a natural step forward to me when I left OSC in 1995. I had a good network of contacts and found enough work that I was really interested in to keep me going. And, I got a lot of experience combining optical design, optical metrology and helping clients take designs and create hardware from them. I found there was a dearth of people who really understood how to go from the output of a design program to an actual optical system. They also didn't understand what was easy to make and what wasn't. Those of us doing metrology know you can only make something as good as you can test it. But most folks just out of school running a lens design program don't yet have a feel for what can be made. I consulted for a lot of small companies along the way, and also had some really interesting large projects.

The first large project I worked on was as the optics consultant for the LIGO (Laser Interferometer Gravity-wave Observatory) Core Optics for 15 years. I helped them hone their specifications, find vendors who could make these state-of-the-art surfaces, and then helped them set up measurement systems to verify the finished surfaces. Each step of the way the LIGO optics pushed the fabricators to improve their processes and testing capabilities. I was not surprised when the project leaders got the Nobel Prize in Physics in 2017.[31]

Around the time I worked on my music degrees, I became one of the editors of "The Optics Encyclopedia", a 5-volume set published by Wiley-VCH covering the entire field of optics.[32] Although there were other editors on board before I got involved, I ended up taking the editorial lead to make sure it got done. I learned a lot about the entire gamut of optics as I edited topics I didn't know much about, and found that this is the type of task that takes way more hours than you get paid for.

7. QUANTITATIVE PHASE IMAGING (QPI)

Another large project I worked on as a consultant and then as employee was with 4D Technology Corp. They had interests in adopting their pixelated phase mask technology to microscopy and biological imaging. I spent five years developing this technology as PI through SBIR grants from NIH and NASA with 4D. We took a system 4D had prototyped for the measurement of surface roughness using the phasecam technology to dynamically measure surface roughness in-situ on large optics and modified it to look at biological samples. Other existing optical systems had taken snapshots of biological sample, but what I wanted to do was to image live moving cells and small biological objects in real time and quantify the optical phase thickness of these objects. Once I got the Phase II SBIR from NIH we hired Goldie Goldstein to work on the project for her dissertation. For four years, the two of us created this system and collaborated with various researchers at the University of Arizona medical school. There looked to be a lot of applications.

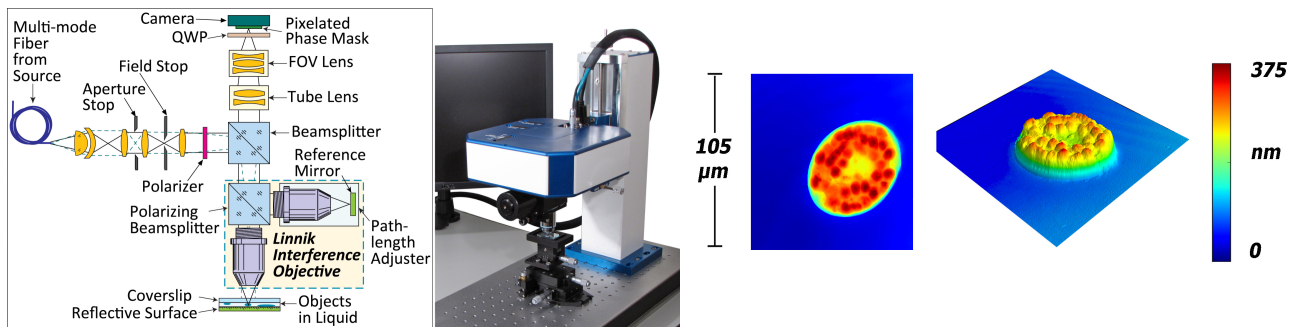


Fig. 10. (left) Optical schematic and (center) photograph of the QPI “BioCam” dynamic interference microscope. (Right) Images show optical thickness maps of protozoa from pixelated phase measurement data.

A schematic of the prototype built for dynamic QPI (quantitative phase imaging) measurement of biological objects is shown on left side of Fig. 10. It consisted of a polarization-based Linnik microscope utilizing simultaneous phase-shifting with the 4D Technology pixelated phase mask. This system was first used to visualize the short time-scale motion of primitive life and single-celled organisms, such as the protozoa in the right side of Fig. 10.[33]

Later we created some very interesting data with a number of biological and medical researchers. We measured blood flow in a live zebrafish, and quantified dynamic changes in the beating of cardiac myocytes (heart muscles cells) in real time before and after applying a drug that sped up the beating (see Fig. 11).[34, 35] The hard part, again, was convincing people that this was worthwhile to add to their research studies. And, we were working with prototypes on a limited budget. When it was time to do the next phase of development after the SBIRs, the project was not continued and the product sat on a shelf. In the end, this was another project that was at least a decade ahead of its time to be viable commercially. There’s still continued interest in this type of technology for studying lab-grown organ models, and I’m sure someone will develop something using the technology of tomorrow that will solve some of the bottlenecks we found with our prototype. And that’s how science goes.

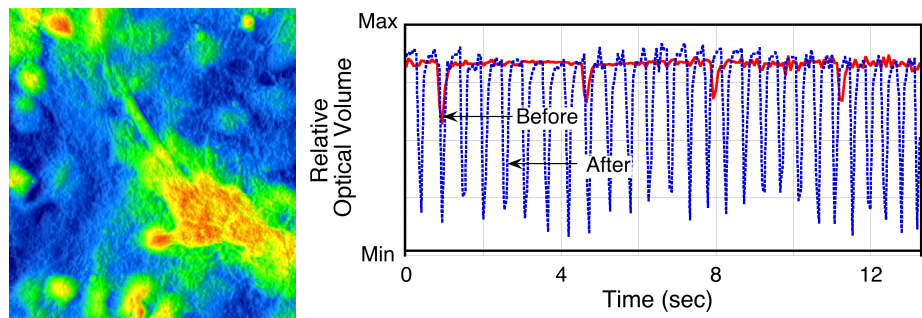


Fig. 11. (left) Phase image of cardiac myocytes quantifying the optical thickness in transmission. (right) Changes in optical volume (dry mass) of myocytes as a function of time before (red) and after (blue) a heart stimulating drug applied showing quantitative measurements obtained in real time.

8. MORE FUN WITH CONSULTING

For the past 11 years I've been focused on consulting rather than research so I've had more time for music. I've had a lot of interesting consulting projects and balanced that with a number of community music groups where I perform and one where I'm the music director and conductor. One direction that has shifted is that I do as much optical design these days as I do software and algorithm development. It's a nice mix working on different projects.

One thing about getting older is I don't feel like I have to prove myself anymore. That's a freedom I wish I had decades ago. Having seen so many different optics problems and challenges helps me help my clients solve their issues and improve their designs so they can have better optical systems. Another thing about consulting is I can see the fruits of my work out in the real world rather than wondering when my research ideas will ever come to fruition in the commercial world. And, more often than I can count, I still get asked "Can you measure that?"

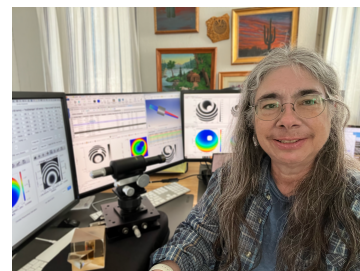


Fig. 12. Consulting.

9. ACKNOWLEDGEMENTS

I wish to acknowledge all the researchers, staff and students who contributed to and collaborated with me on various projects throughout my career. I greatly appreciate your contributions. Space does not permit mentioning every project or everyone's name. I apologize for any errors or omissions.

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