J.A. Woollam Co., Inc.

Ellipsometry Solutions℠

February 2011 | Annual Newsletter | Issue 12

In the past year our company has experienced strong growth. We are now in our 23rd year and we have grown to nearly 50 employees. Of these, nine are applications engineers, dedicated to working with customers to develop measurement and analysis strategies for thin film characterization. We have seven different state-of-the-art ellipsometers in our lab; including VASE, M-2000, alpha-SE, IR-VASE, and VUV-VASE. We are proud to say, our Measurements Lab reached a milestone in 2010 - characterizing over 15,000 samples since the company began.

It was 20 years ago we made our first international VASE sale. This was to Professor Hans Arwin at the University of Linköping in Sweden. Our featured employee, Duane Meyer, has been at our company since the beginning, and helped develop the original VASE instrument. In fact, he and John Woollam delivered that first VASE to Sweden in 1990. Professor Arwin has generously donated this original VASE system back to JAWCo for our museum, as he has replaced the tool with modern JAWCo instruments. His original VASE is still operating and collecting accurate data after 20 years.

LOT-Oriel became our European distributor in the early 1990s. Although headquartered in Darmstadt, Germany, LOT has highly qualified people throughout Europe. Dr. Thomas Wagner has been our primary ellipsometry and technical expert in Europe since joining LOT in 1993. We are happy to count him and his colleagues as our close friends and we enjoy collaborating in both work and pleasure. The former includes regular visits to England and Germany for special workshops on ellipsometry applications and software. The latter often includes sailing or hiking trips. Thomas is always ready for a challenge - whether in ellipsometry or a rigorous mountain hike.

Many current and future applications of Ellipsometry involve measurement of the Mueller-Matrix elements. This method of polarized light analysis was developed by Dr. Hans Mueller, a professor at MIT. We are happy to feature a contributed biography on Professor Mueller by current ellipsometer researchers: Kenneth Järrendahl, Linköping University and Bart Kahr, New York University.

Our featured researcher, Professor Tino Hofmann, represents all that is great about advanced ellipsometry research. His work on far-infrared ellipsometry is leading to exciting new opportunities in THz ellipsometry. His work was recognized at the 2010 International Conference on Spectroscopic Ellipsometry, where Tino received the prestigious Paul Drude Award for significant contributions to THz ellipsometry, especially developments and applications of the optical Hall effect and THz magneto-optics.

20 Year Milestones

Duane Meyer & J.A. Woollam's First International Sale

Duane Meyer is JAWCo's longest, continuously serving employee. Duane has been working in our VASE development group since late 1988 or early 1989 (he can't remember exactly when he was hired, it has been that long.)

Duane has been involved with VASE ellipsometer design and construction since the beginning, so it is no surprise to say if you own a VASE system, Duane's been a big part of it. He can prove it too. Duane still has design drawings and manufacturing records of our earliest systems in his archives. He has been involved in design and development of almost every optical system and subsystem on our VASE ellipsometer; from light sources & lamp housings to monochromators, goniometers, detectors, etc. "Everything but software," Duane says. He has seen it all develop over the years. Duane designed, built and tested the HS-190 monochromator used on all VASE systems since 1997.

L to R: Duane Meyer, Hans Arwin and John Woollam in Linköping, Sweden, December 1990.

An early J.A. Woollam VASE model.

Growing up in Nebraska, Duane earned Bachelor and Master degrees in Electrical Engineering from the University of Nebraska – Lincoln, graduating in 1986 and 1988 respectively. After graduation Duane started working part time in 1988 for the just-founded J.A. Woollam Company. He was hired full time in July 1990 shortly after the company moved out of the University of Nebraska Engineering labs. Duane remembers building wooden tables for instrument assembly at our first location, a former peanut butter factory located about half a mile from the university campus, and about two blocks from our current facility. Duane has been involved with our buildings and facilities ever since, and chairs our company Safety Committee.

Duane opened his archives of our first international sale in 1990 to Prof. Hans Arwin at Linköping University in Sweden (see picture). His records show July 11, 1990 as the date the first parts for the system were ordered. The system took five months to build. For comparison, a modern VASE system is completed in less than half that time. Duane and John Woollam delivered the instrument to Linköping in late December 1990. Duane recalls the trip to Sweden was great, but remembers getting home was an adventure with airport delays, being stuck on runways, etc.

This first VASE system to Sweden is of historical interest as it was our first international sale. It was also the first to use our modern small-size goniometer design, permitting great reduction in instrument size and weight. The design was so good the same goniometers are still used in VASE production today.

Prof. Arwin has used this VASE in his labs for 20 years. He is donating it back to JAWCo as he has upgraded with several modern JAWCo ellipsometers over the years. We plan to display the instrument at JAWCo, so you can see it next time you visit Lincoln, Nebraska.
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Duane is originally from Nebraska, growing up on a farm near Fairbury. He has lived in Lincoln continuously since 1982. In addition to being a great engineer, Duane Meyer is likely the nicest and most patient person you will ever meet. He is a great family man with a wonderful wife, Mary of 37 years, two children, and two grandchildren.

Duane Meyer in 2011, along with the 20-year old VASE, donated by Hans Arwin for our museum.

New Product

VASE Ellipsometer Infrared Spectral Extension to 3300 nm

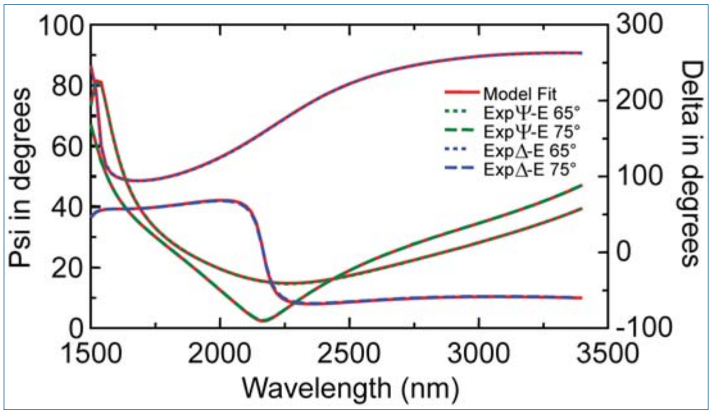
Over the years our VASE ellipsometer has extended into the ultraviolet spectral range, first to 193 nm around 1995, and then into the Vacuum UV to 140 nm for our VUV-VASE in 1999. Now, VASE spectral range is expanding at the long-wavelength end.

A wide variety of improvements to the monochromator, optical fibers, collimating unit, and detectors has resulted in extended infrared operation to 2500 nm and also to 3300 nm.

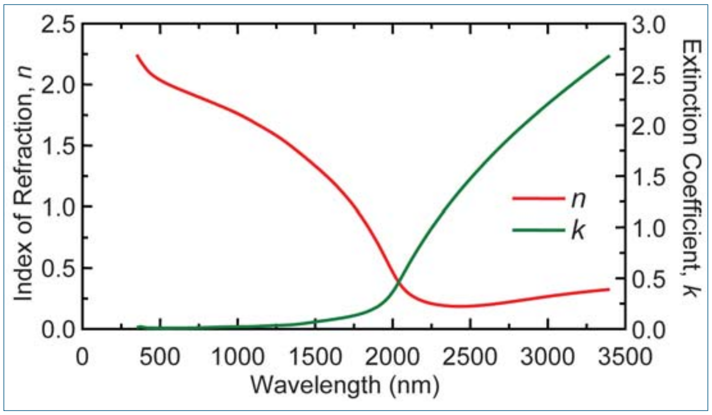
The VASE ellipsometer in our measurements lab is now configured for operation from 193 nm to 3300 nm.

We find the added infrared spectral range is a valuable addition to the instrument, and is useful for applications on low-bandgap semiconductors, photovoltaic films, transparent conductive oxides (TCO), infrared optical coatings, and short-wavelength infrared optics and detectors.

JAWCo now offers the 2500 nm detector as an upgrade to *existing* VASE and VUV-VASE systems, and the 3300 nm detector is available on *new* VASE systems. Please contact *sales@jawoollam.com* or call us if you would like more information.



Thermal SiO_2 on Silicon. Experimental and fitted Ψ and Δ data are shown. Raw data are shown in green and blue, while model fits are shown in red. Beautiful results were obtained out to 3400 nm.



Optical constants n & k for 250 nm TCO film on Glass. Note the plasma frequency (where n=k) near 2000 nm, and increasing absorption (k-values) at longer wavelengths indicating electrical conductivity in the film.

Distributor Spotlight

LOT-Oriel GmbH & Co. KG

The common history of JAWCo and LOT goes back a long time – first discussions between John Woollam and Manfred Berger, who was CEO of LOT at that time, took place in 1990. However, they had met informally years before at Grenoble High Magnetic Field Laboratory while John was a research scientist (before JAWCo was established).

In 1991, LOT started representing JAW in Europe with Dr. Wolfgang Kottler being the first sales engineer responsible for Woollam products at LOT. He ventured out to introduce the VASE to the European market and achieved his first sale in 1991. In May 1992, an official distributor contract was signed, and in 1993, Dr. Thomas Wagner joined LOT as ellipsometer specialist. Since then, Woollam products have become some of the most important items of the LOT product range.

LOT-Oriel's history started in 1970 when the Oriel Optik GmbH was founded in Darmstadt, Germany, as supplier of optical components and sub-assemblies mainly made by US and UK manufacturers. The acquisition of distribution rights for more complex products allowed LOT to expand their activities beyond the optics and small instruments market into related areas like laser machining, spectroscopy, analytical instrumentation, nanotechnology, biotechnology, etc.

Regional growth was initially focused on the German-speaking part of Europe, Italy and the Eastern European countries. In 1991, the LOT-Oriel group was finally established as it is today - covering all European markets and Russia. In 2007, LOT-Oriel merged with one of their main suppliers, Quantum Design, Inc (QD), a leading manufacturer of advanced material characterization instruments.

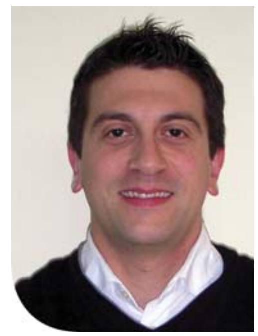
The headquarters of the LOT-Oriel Europe group is located in Darmstadt, Germany. They feature both a well-equipped ellipsometer laboratory and a large service stock. With a large group of highly qualified sales, applications and service staff, LOT-Oriel GmbH can efficiently handle application and service support, providing immediate help for both hardware service and data analysis.

LOT has sales engineers dedicated to ellipsometer products in all European countries and Russia, either as employees of LOT directly or of LOT's sales partners like LAO in the Czech Republic or Optomek in Turkey.

Germany Office From left: Alexandra Foos (Service), Ralf Siegel (Service & Application), Thomas Wagner (Sales & Application), Inga Potsch (Service & Application), Patrick Lindemann (Service), Arjeta Bujari (Sales), Katharina Seehöfer (Sales).

Heath Young
U.K. Sales

Lionel Sudrie
France Sales



Stefano Schutzmann
Italy Sales

LOT frequently organizes ellipsometry seminars and training courses at their premises. Software training courses are held each Spring and Fall on WVASE32® and CompleteEASE®, respectively. Apart from that, LOT technical staff attend several conferences and trade shows a year. For more information, please visit: www.lot-oriel.com

L to R: Thomas Wagner (LOT GmbH), Blaine Johs and Jeff Hale (both JAWCo) during a hiking trip through the Grand Canyon and Zion National Parks.

Metamaterials & the Meta-6 Layer

Tom Tiwald

For ellipsometry, we usually consider only the electric-field component of the electromagnetic (EM) wave interaction with the material. We ignore the interaction of the wave's magnetic-field component at optical frequencies because atoms and molecules tend to have a weak magnetic response to the rapidly changing fields of EM waves at optical frequencies. Thus we usually consider only *dielectric* response (*permittivity*) and ignore magnetic *permeability*.

However, certain kinds of metamaterials change all of that. Metamaterials consist of an artificially-created array of small structures or particles, usually smaller than the measurement wavelength. These structures or particles can be considered "artificial atoms" or "meta-atoms", with properties tailored to interact with incoming EM waves in ways generally not observed in naturally occurring materials.

The Split Ring Resonator (SRR)

The split ring resonator (SRR) illustrates this point. Each SRR shown in Figure 1 is a miniature inductive-capacitive circuit, with the inductor being a single winding of a wire coil, and the capacitor formed by the gap at the split of the wire[1]. Both Magnetic and Electric components of the incident light interact with the rings.

Current is induced in the ring by *incident H-fields* via the time-dependent magnetic flux enclosed by each ring, and *by incident E-fields* via a voltage drop across the gap surfaces.

At the same time, *the constantly varying current* in the ring *induces a magnetic dipole moment* and *an electric polarization* which interacts with the incident H-fields and E-fields, respectively. The polarization is induced at the gap capacitor, and also by generating time-dependent magnetic fields.

These interactions are frequency (wavelength) dependent with a resonant frequency of $\omega = 1/\sqrt{LC}$. The strength of the resonance partially depends upon the metal resistance, which will dampen the effects. The value of R, L and C depends upon the material properties and dimensions of the SRR.

We can summarize these couplings between the electric field **E**, magnetic field **H**, electric displacement field **D** and the magnetic induction **B** using the constitutive material equations:

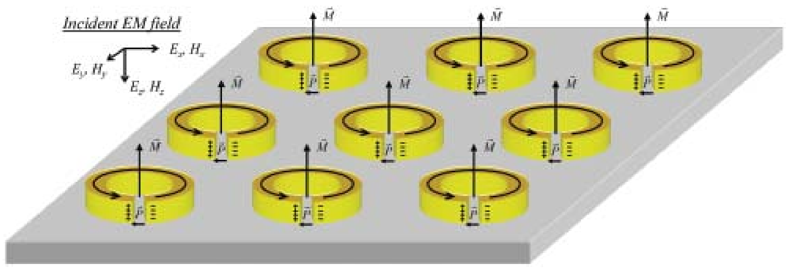


Figure 1. An array of single Split Ring Resonators (SRR's).

$$\mathbf{D} = \varepsilon_o \varepsilon \mathbf{E} + \frac{\gamma}{c}\mathbf{H} \qquad (1)$$

$$\mathbf{B} = \frac{\zeta}{c}\mathbf{E} + \mu_o \mu \mathbf{H} \qquad (2)$$

where c, ε_o, and μ_o are the vacuum speed of light, permittivity, and permeability, respectively. Here, ε is the relative dielectric permittivity and μ is the magnetic permeability; while γ (gamma) and ζ (zeta) are the chiral (or gyrotopic) terms and represent cross-coupling of **H** into **D** and **E** into **B**.

There are other SRR designs, including square rings, u-shapes, etc., as well as two or more rings arranged side-by-side or concentric, or in combination with rods and other elements. Besides SRR's, other geometric arrangements can create time-varying magnetic and electric dipole resonances. These include pillars or rods, crosses, "fishnets", nanorod gratings and other configurations.

Not all metamaterial designs create magnetic dipoles that interact with the incident **H**-fields. Many of the unusual properties can be duplicated or approximated from purely dielectric materials where Re(μ) is either very large or very small, and either positive or negative in value.

Among the unusual optical properties exhibited by metamaterials, perhaps the most frequently discussed is *negative refractive index* (blue box, page 11). Potential applications for metamaterials include frequency-selective surfaces, antenna configurations and invisibility cloaks that hide objects from electromagnetic field probes.

Metamaterial Analysis & Meta-6 Layer

Any complete model of metamaterial structures must be able to model all four relative constitutive functions: ε, μ, γ and ζ from equations (1) and (2). Furthermore, most

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Featured Researcher

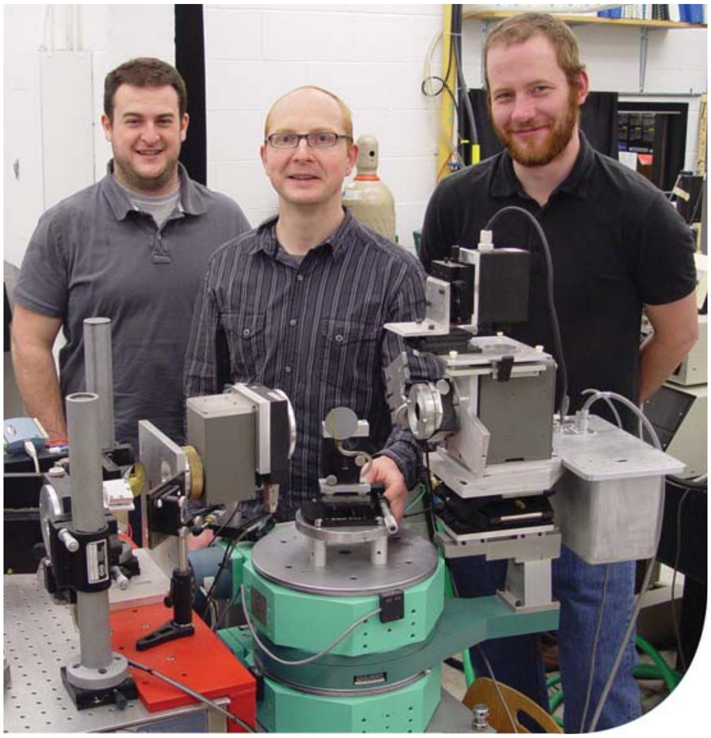
Research Assistant Professor Tino Hofmann

http://ellipsometry.unl.edu

Originally from Grimma, Germany, Tino Hofmann has been generating excitement in the ellipsometry community with research in Terahertz spectroscopic ellipsometry (THz-SE). His experience with ellipsometry started as a graduate student at the University of Leipzig in 1999. There, he employed far-infrared ellipsometry to study InAs monolayers for his diploma thesis research titled "Infrared Spectroscopic Ellipsometry and Raman Spectroscopy on III-V-Semiconductor Superlattices." His advisors were Profs. Bernd Rheinländer and Mathias Schubert and the experimental data were acquired with the far-infrared ellipsometer prototype built by Dr. Daniel Thompson at the University of Nebraska-Lincoln. Back then, the main research interests were phonon frequencies, strain, free-charge carrier properties and intra-band transitions. The far-infrared is important as lower frequencies can interact with these heavier semiconductor atoms.

Tino later received his Ph.D. for "Far-infrared spectroscopic ellipsometry on A-III B-V semiconductor heterostructures." Most of his research revolved around phonon resonances and free-charge carrier properties in III-V semiconductor heterostructures, but also optical birefringence caused by CuPt-ordering in ternary and quaternary alloys in the visible spectral range. The samples were grown in Leipzig by one of the pioneers of metal organic vapor phase epitaxy – Dr. Volker Gottschalch. In the beginning, he was working on an in-house setup to determine the small birefringence of CuPt-ordered GaInP and AlInP in the visible spectral range. His advisor, Mathias Schubert, had designed the setup for transmission experiments, and Tino was developing the software which allowed them to make reflection measurements using on-sample calibration schemes for the optical elements. They used HP-VEE (a visual software development environment) running on a 486 PC to control the hardware. Patience was a necessity!

Collaboration with Professor Schubert continues today, but half way around the globe as both have relocated from Leipzig to the University of Nebraska-Lincoln (UNL). Tino and two graduate students of the UNL



Tino with graduate students, Alex Boosalis (left) and Philipp Kühne (right), standing behind their THz-SE.

Complex Materials Optics Network (Philip Kühne and Alex Boosalis), are working together with Schubert on the development and application of THz-SE. This intriguing new spectral range considers wavelengths in millimeters rather than microns or nanometers. They currently focus on the application of ellipsometry in the 3 to 0.2 mm (0.1 to 1.5 THz) wavelength range for the investigation of semiconductor materials. Tino feels that ellipsometry in this long wavelength range is still in its infancy – maybe comparable to the stage where infrared ellipsometry was about 15 years ago. The materials being investigated range from silicon junctions (where carrier profiles in multilayer structures are determined) to two-dimensional electron gasses in high mobility electron AlGaN/GaN transistors and even graphene (a monolayer of graphite).

The THz spectral range offers numerous interesting "playgrounds" for ellipsometry. The precise determination of optical properties in the THz spectral range is very important. Tino sees much potential in determining electrical properties in a frequency domain which has unique applications in the semiconductor industry, especially with the unique ability to provide information on multi-layered structures. The THz group has not yet looked at the optical response of organic molecules, but initial absorption measurements have shown intermolecular vibrations in the THz spectral range. This area is of great interest in pharmaceutical industries and life sciences in general.

Tino has already been recognized for his unique contributions to the field of ellipsometry. At the 5th International Conference of Spectroscopic Ellipsometry (ICSE-V), he received the Paul Drude Award, which is given "to a young scientist for exceptional contributions to the development and application of spectroscopic ellipsometry." Tino was selected "for his unique contributions with strong focus on development of far infrared and Terahertz ellipsometry, the optical Hall effect and numerous applications on the determination of phonon and free charge carrier properties in semiconductor layer structures". A full description of the award recognition and selection can be viewed at www.icse-v.org. Of this award, Tino states, "It is a great honor to receive this award from our community. Of course the work was only made possible in collaboration with friends and colleagues at many places, but mostly the Universities of Nebraska-Lincoln and Leipzig, and the Woollam Co. I have the great honor of working together with Mathias Schubert and Craig Herzinger for a long time now. One can hardly imagine a better combination of mentors!"

While Tino attends many conferences (including American Vacuum Society, Materials Research Society, and American Physical Society), he has enjoyed the past ICSE meetings tremendously because of the small conference size, broad range of ellipsometry applications, and high quality presentations. Tino recognizes the importance of international conferences in education, and supports international conference participation for his graduate students.

Tino's free time is dedicated to his family. He and his wife, Juliane, enjoy time with their 18-month old son, Oswin. In particular, the Hofmanns enjoy the outdoors and visiting national parks. They have been on several hiking trips to national parks in California and Colorado, and have planned a summer 2011 RV trip to national parks of the Canadian Rockies. His favorite park thus far is Redwood National Park in northern California, where "walking underneath the giant trees (many of them exceeding 100 m in height) is a wonderful experience and hard to cast in words."

Dr. Hofmann's friends at JAWCo foresee his research having a monumental impact on future SE applications, perhaps even as monumental as one of the California redwood trees.

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Tino and Juliane in one of their favorite US national parks: Redwood National Park in California. Behind them, you can see a (very small) part of a coastal redwood tree.

Hans Mueller (1900-1965)

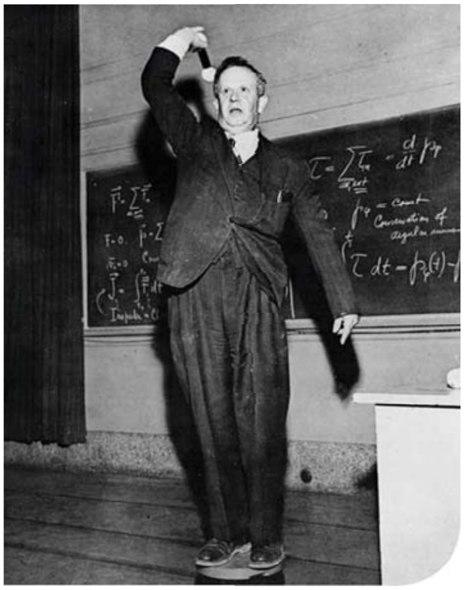
by Kenneth Järrendahl[a] and Bart Kahr[b]

[a] *Department of Physics, Chemistry and Biology, Linköping University, Linköping, Sweden, kejar@ifm.liu.se*

[b] *Department of Chemistry and Molecular Design Institute, New York University, New York City, USA, bart.kahr@nyu.edu*

We are happy to offer this contributed biography exploring the life and work of Hans Mueller. It is appropriate to honor the man whose development of the Mueller matrix has become increasingly popular in today's ellipsometry community for measuring anisotropic and partially polarizing materials.

Students of the Stokes-Mueller calculus are confronted with an imbalance: the Stokes vector is named for Sir George Gabriel Stokes, one of the great Victorian polymaths known to most scientists, while the Mueller matrix is named for Hans Mueller, an MIT professor who published sparingly and about whom biographical information is hard to find. Here, we aim to satisfy the curiosity of those who ask, "Who was Hans Mueller?"



Mueller during a physics demonstration. (With permission of MIT Museum.)

Hans Müller* was born in the village of Amriswil in the canton of Thurgau in Switzerland on October 27, 1900. He was the son of Ernst Müller, a farmer, and Mathilde Müller (born Meier). His early years were spent at the primary and secondary schools of Amriswil. In 1916, he began technical studies in the canton capital Frauenfeld and received his high school degree (Reifezeugnis) in the autumn of 1919. His undergraduate and graduate education were conducted at the Eidgenossische Technische Hochschule (ETH) in Zürich where he received a teacher's diploma in science and mathematics in 1923. During the following two years, he worked as a graduate student assisting the Nobel laureate Professor Peter Debye and also Professor Paul Scherrer. In the beginning of 1925, Mueller accompanied Debye on a visit to the Massachusetts Institute of Technology (MIT)[1], but Debye returned to Switzerland alone as Mueller accepted a position as a research associate in the MIT Department of Physics.[2] He completed his ETH dissertation (1928) "Zur Theorie der elektrischen Ladung und der Koagulation der Kolloide" (On the Theory of Electric Charge and Coagulation of Colloids)[3] while working in Cambridge.

The colloidal state of matter was one of the most active areas of physical chemistry in the 1920s.[4] With his doctoral degree, Mueller was promoted to assistant professor, and in 1935 had earned the rank of associate professor.[5] During the academic year 1937–38, he took leave as a Guggenheim Fellow at the Cavendish Laboratory at Cambridge University. In 1942, he was promoted to full professor.[6]

At MIT, Mueller continued his work on colloids,[7-13] but was also beginning to investigate the dielectric and optical properties of crystals and studied the photoelastic effect, a curious foreshadowing of the use of PEMs to deliver Mueller matrix elements.[14-18] Mueller's papers on Rochelle salt, the first ferroelectric crystal, summarized the experimental studies of this substance.[19-23] Apparently, Mueller, in connection with the work on Rochelle salt, coined the term *ferro-electric*,[19] later written *ferroelectric*.[20]

Mueller was one of MITs most popular teachers.[24] He had a major impact on the physics curriculum[25-28] and overhauled one of the Institute's anchor courses, freshman physics.[29] His teaching style included vivid gestures and a loud voice with strong German accent. When Mueller broke his wrist while cranking a Ford automobile, some students assumed it must have happened during a lecture;[30] he was known to flap his arms wildly when animating electromagnetic waves. In all respects, Mueller was highly engaged in the life of MIT, and expressed great concern for the "boys" that were under his charge.[31-35]

* We use his anglicized surname "Mueller" elsewhere, as he did professionally.

As the premier engineering school in the United States, life at MIT was upended by the second world war. Many of the professors and students were drawn into unfamiliar territory. Mueller was involved in standardizing human serum albumin solutions by light scattering, a necessity during the scale up of blood plasma proteins in advance of the invasion of Normandy.[36] His work on light scattering played a role in the development of his eponymous matrix introduced in 1943.

Mueller was motivated to place optics upon a phenomenological foundation, measurements of light intensity, as opposed to the assumption of the wave equation. His matrix formalism was not well documented at the time, but appeared in a now declassified report,[37] and was presented in course 8.262 "Foundations of Optics" at MIT during 1946–1949. The matrices were also presented at the winter meeting of the Optical Society of America 1948[38] and in the thesis of Mueller's student Nathan Grier Parke III, among other doctoral and bachelor of science students.[39] As recalled by his chairman, J. C. Slater, "[Mueller] *has been following a lead which originated from his work on scattering of light during the war. In this study, Mueller developed an interesting mathematical theory of optical instruments and their relation to polarized light. In this theory, an optical instrument is replaced by a linear transformation applied to a vector representing the state of polarization of the light. By extensions of this theory, one can get answers to very complicated problems in the effect of instruments, particularly polarizing instruments, on the state of polarization, problems of great interest to the optical profession. This work, which has not yet been published in an extensive form, is essentially theoretical; Professor Mueller has not been doing experimental work recently, though he hopes to return to it."*[40]

Soon after the end of spring term, on June 10, 1965, Hans Mueller died unexpectedly at his home in Belmont, Massachusetts.[41] He was survived by his wife, Inez, and daughter, Agneta. Mueller was remembered by colleagues as *"a superb teacher and one of the most beloved members of our faculty."* In the "footnotes" section of *The Tech,*[41] a student commemorated Mueller with these words: *"Those of us who were lucky enough to draw recitation sections under 'Hans' will miss him; those who weren't that lucky missed something rare."*

The authors are currently working on a more detailed paper on the life and works of Hans Mueller. Any information on the subject is welcome.

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...continued from page 5.

metamaterials are anisotropic; and therefore ε, μ, γ, and ζ are 3x3 tensors. The constitutive material equations now become

$$\begin{bmatrix} D_x \\ D_y \\ D_z \end{bmatrix} = \varepsilon_0 \begin{bmatrix} \varepsilon_{xx} & \varepsilon_{xy} & \varepsilon_{xz} \\ \varepsilon_{yx} & \varepsilon_{yy} & \varepsilon_{yz} \\ \varepsilon_{zx} & \varepsilon_{zy} & \varepsilon_{zz} \end{bmatrix} \begin{bmatrix} E_x \\ E_y \\ E_z \end{bmatrix} + \frac{1}{c} \begin{bmatrix} \gamma_{xx} & \gamma_{xy} & \gamma_{xz} \\ \gamma_{yx} & \gamma_{yy} & \gamma_{yz} \\ \gamma_{zx} & \gamma_{zy} & \gamma_{zz} \end{bmatrix} \begin{bmatrix} H_x \\ H_y \\ H_z \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} B_x \\ B_y \\ B_z \end{bmatrix} = \frac{1}{c} \begin{bmatrix} \zeta_{xx} & \zeta_{xy} & \zeta_{xz} \\ \zeta_{yx} & \zeta_{yy} & \zeta_{yz} \\ \zeta_{zx} & \zeta_{zy} & \zeta_{zz} \end{bmatrix} \begin{bmatrix} E_x \\ E_y \\ E_z \end{bmatrix} + \mu_0 \begin{bmatrix} \mu_{xx} & \mu_{xy} & \mu_{xz} \\ \mu_{yx} & \mu_{yy} & \mu_{yz} \\ \mu_{zx} & \mu_{zy} & \mu_{zz} \end{bmatrix} \begin{bmatrix} H_x \\ H_y \\ H_z \end{bmatrix} \quad (4)$$

Equations (3) and (4) are embodied in the *Meta-6* layer, which is included in all the newest versions of WVASE32®.

The user can define frequency-dependent functions to describe the various complex dielectric and magnetic properties of the material, as well as any gyrotopic properties.

One restriction: for most accurate modeling, the meta-material should be homogeneous at the wavelengths of interest, (i.e., the dimensions of the "meta-atoms" << λ). When this is not true, the field equations must be solved using numerical finite element methods.

Figure 2 shows the Meta-6 layer along with the four sub-tensors. In this example the gyrotopic tensors are zero.

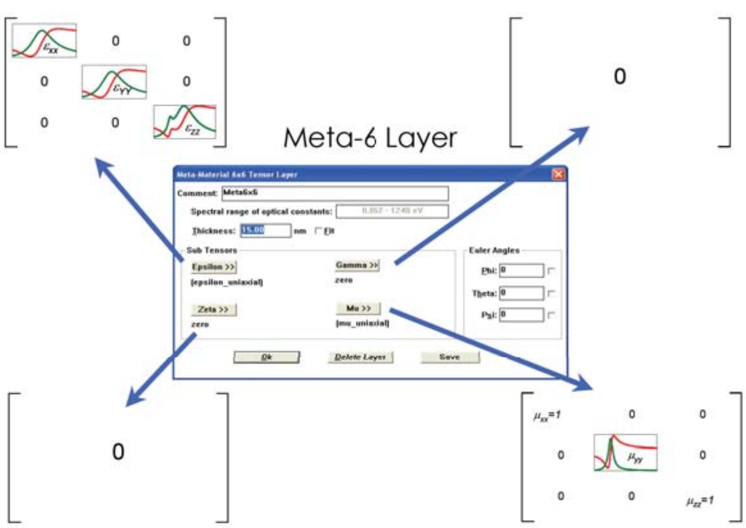

Figure 2. Meta-6 layer and sub-tensors ε, μ, γ and ζ. The sub-tensors are defined in separate "dummy layers".

The sub-tensors are defined in separate layers, which are coupled into the Meta-6 layer. This allows the user to define ε, μ, γ, and ζ tensor functions using combinations of Genosc, User or other layers.

Gold nanorod simulation

In principle one should be able to produce *LC* resonances at visible frequencies by scaling the SRR geometry to about 100nm. Unfortunately, the maximum operating frequency of that design is limited by the metal resistivity and kinetic inductance[1]. To overcome this, many designs take advantage of the surface plasmons (surface charge density waves) that naturally occur on metal surfaces to produce electric and magnetic resonances at visible wavelengths. The incident EM-wave couples with plasmons on the surface of the metal structures, resulting in a virtual circulating current. The circulating plasmons form magnetic dipoles, which interact with the EM-wave's magnetic-field.

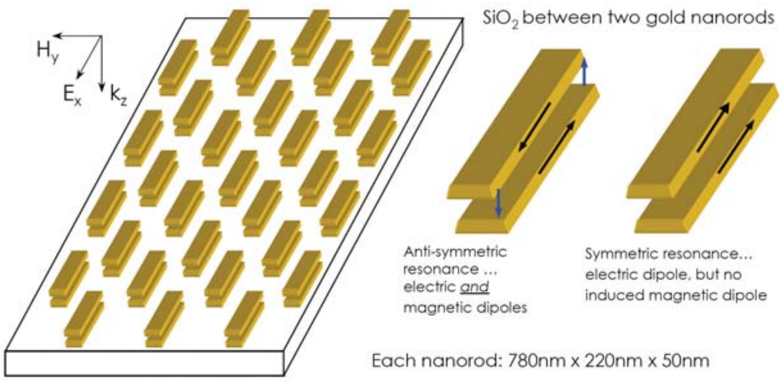

Figure 3. Gold nanorod example. Incident light generates parallel and anti-parallel surface plasmon "current flow" in rods.

An array of gold nanorod pairs (based on a paper by Drachev, et al.[3]) are shown in Figure 3. The E_x-component of incident light introduces horizontal plasmon "currents" in the structures. A symmetric resonance occurs at frequencies where the oscillating E_x-fields cause symmetric plasmon "current" flow in adjacent pillars. An anti-symmetric resonance occurs at frequencies where the oscillating E_x-field supports an anti-symmetric plasmon "current" flow in adjacent pillars. In the dielectric tensor, ε_x will have two Lorentz resonances, symmetric and anti-symmetric, at different frequencies.

Because the anti-symmetric currents mimic a rotational current, a magnetic dipole resonance exists along the y-direction, μ_y. No magnetic dipole exists along the other directions, so $\mu_x = \mu_z = 1$. The permeability tensor would look something like Figure 4.

Figure 5 shows simulated normal-incidence transmission data for the nanorod model. This is only one of many possible data types that can be acquired with an ellipsometer and modeled using the Meta-6 layer.

Metamaterials are usually anisotropic and are often depolarizing; meaning that they usually require either generalized ellipsometry (g-SE) measurements or even Mueller matrix ellipsometry (mm-SE).

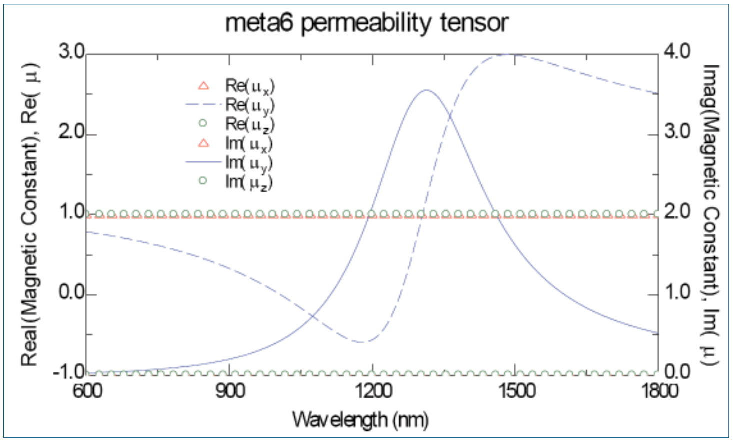

Figure 4. The permeability tensor with magnetic dipole resonance along μ_y.

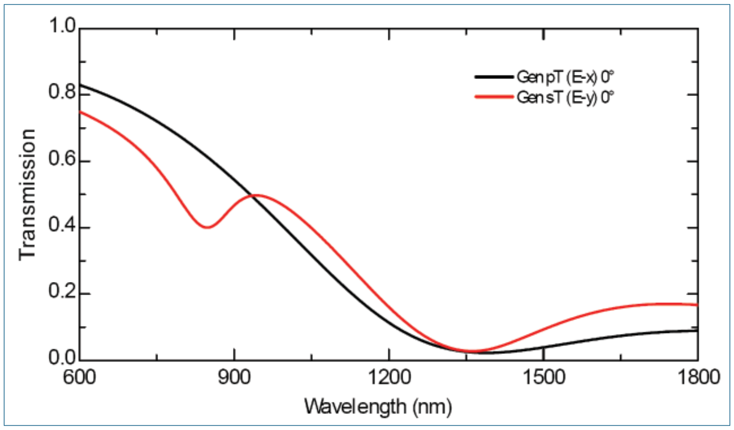

Figure 5. Simulated Transmission for the gold nanorod example.

References:

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Negative Index of Refraction

Negative index materials, or NIM's, are metamaterials with a refractive index < 0 over some frequency range. A negative index occurs when both Re(ε) and Re(μ) < 0; therefore materials that possess this property are also called *double-negative* materials (DNM's). Remember that the index $\tilde{n} = \sqrt{\tilde{\varepsilon}\cdot\tilde{\mu}}$. Since ε and μ are generally complex numbers:

$$\tilde{n} = \sqrt{\tilde{\varepsilon}\cdot\tilde{\mu}} = \sqrt{|\varepsilon||\mu|}\, e^{i\left(\frac{\theta_\varepsilon+\theta_\mu}{2}\right)}$$

Veselago[2] showed that when Re(n) < 0; ***E***, ***H***, and the wavevector ***k*** follow a *left-handed* rule instead of the *right-hand* rule, as shown in figure NIM-1. However, the Poynting vector is ***S = E x H***, thus ***k*** and ***S*** can point in opposite directions when light travels through negative index materials. As a consequence, the angle of refraction is negative when $n < 0$, as predicted by Snell's law. See figure NIM-2.

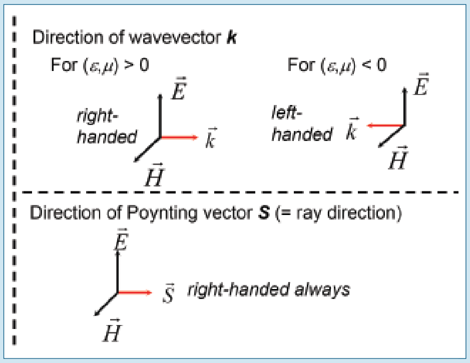

Figure NIM-1. Directions of **k** and **S** for (ε,μ) > 0 and (ε,μ) < 0.

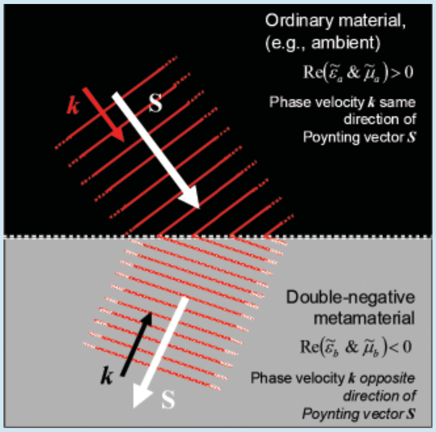

Figure NIM-2. Planes of constant phase (red lines), k and S for light beam entering double-negative material. Angle of refraction is negative, or to the left.

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Taiwan
Titan Electro-Optics Co., Ltd.
14 Fl., No. 19-11
San-Chung Road
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Japan
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Ph: 81-3-3220-5871
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Singapore
Crest Technology Pte. Ltd.
4 Loyang Street
Loyang Industrial Estate
508839 Singapore
Ph: 65-6546-4811
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marcus@crest-technology.com
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Italy
L.O.T. Oriel Italy, s.r.l.
Via Francesco Sapori 27
Rome, Italy 00143
Ph: 39-06-5004204
Fx: 39-06-5010389
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L.O.T. Oriel France
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Australia & New Zealand
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info@wizoptics.com
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