Terahertz Pioneer: Philippe Goy

"If You Agree With the Majority, You Might be Wrong"

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PHILIPPE GOY[1] was one of nine brothers and sisters that grew up together in a small village 30 km east of Lyons in southern France. His grandfather, and his father were mill owners and operators and they occupied a large complex of buildings on a small tributary of the Rhone River. This was an ideal environment for a boy who liked to tinker and to work things out for himself. The mill was one of the first in the area to produce and distribute electricity. With two large turbines yielding more than 80 kW, Philippe's grandfather illuminated both his own residence (using AC) and neighboring homes and commercial ventures, by selling DC power. During World War II this capability was particularly important. It was also fertile ground for Philippe, who had an early interest in radio, and used the electricity, an old aircraft transmitter, and a 50 m antenna to broadcast MHz signals to all his neighbors. At age 14, he was assembling various electronic instruments from popular magazine designs, including a pair of 70 MHz walkie-talkies used in his boy scout patrol during excursions. This early interest in electronics, coupled with a natural talent in mathematics, landed Philippe at preparation for the Grandes Écoles, a precursor to the Ecole Normale Supérieure (ENS), which would become his home for most of his career in science.

Philippe was encouraged to major in mathematics because it was the most highly regarded academic path in 1950's France. However, he was more interested in Physics, (*it helped that his physics teacher liked him more than his mathematics teacher*). Therefore, in 1961, at the age of 20, he entered ENS in Paris to study physics. At ENS, Philippe was given a room and a small salary in exchange for his training to be a teacher or a state-employed researcher for 10 years. At the ENS Physics Department laboratories, he was impressed by their collection of high frequency French-made backward wave oscillator (BWO) tubes (the head of Thomson CSF was a former ENS student). These were called *carcinotrons*—derived from the route of the Greek word for Cancer (crab) $\kappa\alpha\rho\kappa\iota\nu o\varsigma$, but actually referring to the behavior of the freshwater "crayfish" because the RF energy in a BWO propagates in a direction that is opposite to the flow of electrons from the injection gun, like the movement of the crayfish, which often crawls slowly backwards in the flowing water [2].[2] Note that only two countries in the world at that time: the Soviet Union and France, were producing such BWOs, these unique tunable sources in the millimeter–submillimeter domain. The French produced carcinotrons covered frequencies from 30 GHz all the way up to 700 GHz, and Philippe was to make great use of these sources for his thesis work, and later for his research on quantum behavior in Rydberg atoms.

PHILIPPE GOY

When Philippe began his thesis work in 1965, ENS was a very politically active school and leaned heavily to the "*left*." Regis Debray, French philosopher and close associate of Che Guevara, was a student leader (Debray was arrested in Bolivia in 1967, as was Guevara, and spent 3 years of a 30 year sentence in prison before being released upon international pressure in 1970). However the emphasis on Marxist dogma at ENS (including Mao Zedong's) only served to convince Goy that

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[1]After meeting at the Gare du Nord, in the early afternoon of March 28th, 2013, Philippe Goy escorted me back to his modest apartment on a quiet street in the Montparnesse region of Paris. After admiring his photography, his collection of West African art, the science fiction books he had written, and his many other diversions from the world of quantum physics and THz instrumentation, we sat down for a lengthy interview that lasted well past *le temps du repas*. Afterwards, we enjoyed a wonderful concert at the new Paris Opera house. Philippe is an individualist who is perfectly in keeping with a well-cited quote of Louis Pasteur (one of Philippe's stated mentors), *"dans les champs de l'observation, le hasard ne favorise que les esprits préparés,"* in the field of observation, chance favors only the prepared mind [1]. Dr. Goy enjoys working things out for himself and thinking about problems in ways that do not necessarily follow the crowd. I was happy to follow along with his stories that cover his career, and constitute the kernel of this *THz Pioneer* article.

[2]See [2, p. 354] for partial definition origin

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"*thinking for oneself*" was the most important dogma for a serious student.

Philippe's thesis advisor, Julien Bok (director of the Solid State Physics laboratory at ENS) introduced Goy to low temperature physics and suggested his early work on trying to verify high frequency cyclotron resonances in metals (predicted by Mark Azbel' and Emanuil Kaner [3], two students of Ilya Lifshitz—brother of the famous Landau and Lifshitz, authors of the physics text book series). Goy focused mostly on strong electron—phonon interactions in single crystal metals. The studied species included copper, lead, indium, mercury, niobium and nickel [4]–[10] and later bismuth, cadmium and silicon [11]–[13]. When he completed his thesis in 1970, Philippe was given a permanent position in the Centre National de la Recherche Scientifique—CNRS and would be able to continue working at ENS in Paris.

The experimental method that Goy developed for the electron cyclotron experiments, places a plane pure single-crystal metal sample (or semiconductor) in a strong static magnetic field parallel to the surface, and which is illuminated by microwave energy. The Azbel'–Kaner effect predicts that electrons spiraling around the magnetic field lines will interact with the RF field created within the skin depth of the metal by the applied microwaves, when the RF frequency is close to the cyclotron frequency, or close to an harmonic of it, since the electrons are "blind" to the microwaves as they pass into the metal bulk. The multiple resonances that could be observed at field strengths of $B_{\mathrm{cyclotron}}/n$, n integer, offered a significant measurement advantage with the limited magnetic fields available at that time. The interaction affects the surface impedance, and hence the absorbed power in the conductor, which was detected with an helium cooled Allen–Bradley resistor—type bolometer [14] glued onto the sample. To increase the sensitivity, a Fabry–Pérot RF cavity was added by placing a spherical mirror in front of the plane sample.

Accurate analysis of the data requires precise absorption line profiles, and hence very narrow RF line widths—which the carcinotrons supply. These measurements allowed, for the first time, observation of cyclotron mass dependences on frequency and on temperature, and of correlated relaxation times in metals with low Debye temperature (phonon contribution to the low temperature heat capacity), and helped clarify models of electron–phonon interactions [15].

It should be noted that the carcinotrons at ENS were not found in every research lab. They were extremely expensive (30k$-90k$ each), required high operating voltage (4–12 kV) and current (10's of milliamps), continuous water cooling for the very high current density anodes and collectors, and they were very short lived (warrantied for only 300 hours, although generally lasting for thousands hours when carefully driven). Goy remembers with relish receiving a call from a Thomson CSF executive while he was involved in the electron cyclotron measurements. The Thomson representative asked him to please come and collect some tubes that were being held in a leaking factory warehouse in the suburbs of Paris, as no one at Thomson had any specification papers on the tubes, nor were they planning to use them any longer. He gladly drove his car to the site, and loaded it up with more than 10 tubes—*market value of more than half a million US dollars at the time!* Almost all of these he reconditioned, wired up, and later was able to use in his experiments at ENS.

The complex RF sampling instrument that Goy had assembled and used for the electron-phonon interaction measurements turned out to be a perfect tool for probing the weak electromagnetic forces (in the millimeter- and submillimeter-wave energy range) that hold outer valence electrons $(n \approx 30)$ in place in highly excited atoms (Rydberg orbitals). When Serge Haroche (2012 Nobel Prize in Physics for work on quantum decoherence) came out of Claude Cohen-Tannoudji's (1997 Nobel Prize in Physics for work on laser cooling and trapping of atoms) group at ENS in the early 1970's, and began working on Rydberg atoms, Goy's millimeter and submillimeter-wave expertise was the perfect complement to Haroche's experience with tunable optical lasers (used to excite the atoms into the Rydberg states).

The two researchers, together with Claude Fabre, and later with Michel Gross, Jean-Michel Raimond (also at ENS) and Luigi Moi (from University of Pisa, later department chair in physics at University of Siena, Italy), started to study the optically excited states $(n = 23 - 41)$ of sodium [16] with an ultimate goal of a more accurate determination of the *Rydberg constant* (ionization energy of the hydrogen atom) [17], as well as measurements of quantum defects, fine structure constants and polarizability [18]. These Rydberg atoms are often known as "giant atoms" because the orbital diameter of the outer electron can be more than 1 micron. Due to this large diameter and weak orbital coupling, they are easily excited by millimeter- and submillimeter-waves, and make extremely sensitive detectors.

The ENS team used a pair of dye lasers to bump the electrons of the alkali atoms, Cs and Na, from the ground state to the first excited P state, and then to the desired Rydberg level. This would cause a population inversion in a very small number of atoms. Despite the small number of atoms in the inverted population, there was very strong coupling of these giant atoms to the applied microwaves. Adding a high-Q Fabry–Pérot cavity tuned to the frequency difference between the upper (populated) and lower (empty) states, triggered super-radiance—a spontaneous decay cascade that produced a well-defined RF emission in the millimeter- and submillimeter-wave bands.

This super-radiance, and also similar MASER action (single frequency emission), was taking place with a total energy output of between 1 and 100 eV only, corresponding to power levels of 10^{-13} to 10^{-11} W [19]. The weak, very narrow band emitted millimeter- and submillimeter-wave signals had to be measured using a sensitive Schottky diode heterodyne detection scheme that had been developed for Radio Astronomy applications [20].

The ENS instrument had a frequency resolution of around 30 MHz and the team went on to show how their technique could be used to make sensitive detectors for Rydberg transitions [21]–[23], as well as performing many pioneering experiments on the spectral features and the interactions of these very small groups of atoms with black body radiation [24]–[26]. They also performed many pioneering experiments on the spectral features of a range of different atomic configurations and molecules [27]–[34].

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The observation of cavity-enhanced single-atom spontaneous emission [35], was the first in a series of studies on single atoms and single photons. It was a key result on the path to Haroche's 2012 Nobel prize. The observation was made possible after Goy adapted the Fabry–Pérot setup he had assembled for his thesis on cyclotron resonance in metals, by introducing superconducting niobium mirrors.

In these early experiments, the storage time for photons in the cavity was severely limited by the Fabry–Pérot cavity Q (typically 10^6). In order to get down to single atom events, already observed [35], but with multiple interactions with one (or a few) photons, the Q had to go up several orders of magnitude, to at least 10^8. This also meant that the frequency resolution and counting accuracy for the RF signals had to improve—to below kHz levels (one part in 10^8).

At this time, 1986, Goy was helping Michel Brune complete his thesis work on a 2-photon Rydberg atom MASER that calculations showed was possible inside a cylindrical cavity with $Q > 10^8$, tuned at the very precise transition half-frequency of 68 GHz. The cavity preparation required a much more sensitive measurement system than was available at ENS (the usual technique of measuring the cavity transmission was not possible because of the extreme undercoupling of input and output required to avoid high-Q damping). Goy had the idea of using high order harmonic multiplication on the source side, and high order harmonic mixing on the detector side, in order to realize a very high frequency resolution millimeter spectrometer that could be swept across the full range of an ultra high-Q cavity resonator and maintain sub-kHz resolution. The final detection frequency was arranged to be in the audio band, which Goy hoped to be able to record with simple earphones.

Goy put together a prototype, and together he, Jean-Michel Raimond, and Michel Brune, drove out to CERN (Conseil Européen pour la Recherche Nucléaire) in Geneva, Switzerland, where specialists could machine the final niobium cylindrical cavity. After helium cooling, the sub-kHz wide resonance had to be found within the much wider (200 MHz) uncertainty of the cavity after machining. By sweeping the RF through the resonance, Goy was able to hear the response when the cavity was tuned. After chemical etching and mechanical pressure to tweak the cavity into its final tuning range, controlled by the millimeter spectrometer, Brune was able to demonstrate the two-photon Rydberg atom MASER [36], [37] and receive his Ph.D.!

This extremely sensitive atomic measurement setup, using the Fabry—Perot with cooled superconductive niobium mirrors (allowing side access to the excited atoms and to the applied fields), was further improved upon, and eventually opened up the field of cavity electrodynamics. It allowed many single atom and single photon experiments that have been used to demonstrate a range of quantum effects from Schrödinger's cat to quantum entanglement. The requirement to perform extremely high resolution swept frequency RF measurements also led Goy to think about other uses for his millimeter—and submillimeter-wave solid-state generator and detector circuitry—and to a rather sharp diversion in his career as a quantum physicist.

Goy realized that the RF pump–probe instrumentation he had developed for characterizing Rydberg states could be used for other applications in the THz region. He first showed off his scalar *millimeter-wave network analyzer* at the HYPER trade show in Paris in 1987 (HYPER comes from the French word "Hyperfréquences," and this show was simply the French equivalent of a *Microwave* trade show). This new all solid-state analytic tool was at first commercially coupled with a generic BWO power supply, being distributed by a small French company, Sielux. However Sielux was to go out of business shortly after the 1987 exhibition.

In the late 1980's CNRS was encouraging scientists to commercialize their inventions in order to show the return on the investment the French government was making to academic research. It was a perfect time to start up a side business. Goy had designed the millimeter-wave system so that it could be easily used by students, and so he formed a company he called AB MILLIMETRE, *ABmm—since it was now as easy as ABC, to perform millimeter- and submillimeter-wave measurements!* He described his new instrument at the 1987 *International Conference on Infrared and Millimeter Waves* [38] and first showed it under the ABmm name at MIOP'88 [39]. By 1989 it could reach 350 GHz with 40dB of dynamic range [40]. Goy sold two instruments that year—one to Germany, and one to Britain—both to research groups involved in solid-state physics experiments.

At this point, Michel Gross was completing his thesis on the Rydberg atom measurements at ENS. As part of the thesis work, he and Goy had developed a novel vectorized (magnitude and phase) heterodyne source/detector locking scheme and circuitry that avoided the need for the expensive high directivity RF input/output directional couplers that were used in all microwave vector network analyzers (and which did not exist above 300 GHz). In this scheme, both source and detector were locked to a low frequency reference (single quartz crystal) using a multiple-stage vector upconverter–downconverter process. A pair of phase locked, and sweepable microwave YIG (yttrium–iron–garnet) oscillators, multiplied up to the 20th harmonic or so, served as the reference for a millimeter-wave harmonic generator, and as a local oscillator for a millimeter-wave harmonic mixer. The signal generator and mixer were arranged to operate on the same harmonic of the YIG through heterodyne receiver selectivity. Signal sampling at all bands was performed through commercial harmonic mixers. To reach large signals beyond, say 250 GHz, strong fundamental oscillators (W-band Gunn diodes or tube-based sources) were added, in order to drive a tunable Schottky diode-based multi-harmonic multiplier (on the source side) and a harmonic mixer (on the receive side), with a set of replaceable high-pass waveguide filters to cut off the undesired lower harmonics. Again, the heterodyne receiver selects the operating harmonic. The genius of the circuit design was in its ability to servo-control and track the individual harmonic outputs and keep them all sorted and locked to a single reference.

Goy and Gross patented, through CNRS, the new vector analyzer circuitry in France in 1989 [41] and received a U.S. patent in 1992 [42]. They presented the new circuitry at a series of conferences [43], [44], for example, and displayed the full vector MVNA at the *15th International Conference on Infrared and Millimeter Waves* in Orlando, FL, USA in 1990 [45]. Goy and Gross then extended the MVNA up to 1000 GHz. More recently, the use of $\times 6 \times 3 \times 3$ multiplication chains (up from 18 GHz),

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made it possible to obtain a dynamic range of 80 dB at this high frequency. In the prior Gunn diode setup, the MVNA could also sweep over a modest frequency range (1–3 GHz), with a large dynamic range −120 dB at 400 GHz. It can also display magnitude and phase information in a variety of formats and performs a diverse set of open-air measurements, from antenna beam patterns to full two-port vector transmission and reflection measurements on samples.

Interest in the MVNA began to take off in 1990, and to date more than 60 have been sold around the world. It should be noted that Philippe and Michel personally built and installed almost all of these systems. As a recipient of unit number 30 in 1996, I can attest to the dedication and personal service provided by both Goy and Gross, who both spent many days (and nights) in our lab at the Jet Propulsion Laboratory, Pasadena, CA, USA, customizing and modifying our system, as well as installing new hardware and software for our many varied applications (measuring emissivity of calibration targets for space applications [46] to vector imaging [47], just to name a couple).

After our discussions, I asked Philippe to tell me about the science contributions that were attributable to the ABmm MVNA. Instead, he had some of his customers send me references. I was overwhelmed by the breadth and detail of the many application areas and scientific contributions for that this instrument has been part of. A select few of these are contained in [48]–[57].

After the release of the MVNA, Goy continued to work on fundamental physics experiments in his group at ENS [58], [59], and he also expanded his collaborations to include laboratories that were using his instrumentation [60]–[68]. In 2007, Goy was forced to retire from CNRS, but he has kept up his office and lab visits and focuses most of his professional time on maintaining, selling and improving his MVNA. He has recently replaced the Gunn diode oscillators and narrow band harmonic mixers and multipliers with new higher efficiency sources and detectors, that provide sweep capability over full waveguide bands between 8 and 1000 GHz.

As we wound up our discussions, we moved onto topics of more general interest. In keeping with Voltaire's concept of a universal man, Philippe ranked his most important subjects as Art, Literature and Science in stated order, with Politics down at the very bottom. His lovely photographs, his six science fiction stories [69]–[74], and his general writings [75]–[77] attest to his breath as a creative person. Dr. Goy has always enjoyed working things out for himself, and thinking about problems in ways that do not necessarily follow the crowd. A favorite quote is *" If you agree with the majority, you might be wrong. "* I was definitely not wrong in including Philippe in this series of interviews with *THz Pioneers*. I hope you will agree.

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Philippe Goy entered the Ecole Normale Supérieure in October 1961, and received the Ph.D. degree in physics in 1970. He served as an assistant professor at Université de Paris from 1965 to 1966 and then took up a permanent research position with the Centre National de la Recherche Scientifique (CNRS) at Department of Physics of Ecole Normale Supérieure (ENS) in Paris, France, where he became Directeur de recherche DR1. At CNRS, Dr. Goy worked on solid-state physics, specifically electron–phonon interactions in metals and semi-metals, followed by ground-breaking experiments in atomic physics involving Rydberg states. His novel helium cooled combined high Q resonator and millimeter and submillimeter-wave source and detector circuits, helped him and collaborators at ENS to make the first high n-transition state measurements on Rydberg atoms, identify super-radiance and MASER action in these giant atoms, and record the first single atom emission in the submillimeter wave frequency range. This work set the framework for, and eventually led to the 2012 Nobel Prize in Physics for colleague and long time friend Serge Haroche. In 1988, Dr. Goy founded a small company—AB MILLIMETRE—to commercialize some of the test and measurement instrumentation that he developed for his academic physics experiments. Along with CNRS colleague Michel Gross, he prototyped and sold first a scalar, and then a full vector network analyzer that could reach frequencies of 1 THz with extremely high dynamic range. This instrument, the ABmm MVNA, has now been purchased by more than 60 research groups and companies around the world and has been continually improved and expanded in capability. The ABmm MVNA is the first fully flexible commercial THz test and measurement instrument and has resulted in hundreds of diverse scientific applications and peer reviewed papers. Although officially retired from CNRS, Dr. Goy continues to work in his company and to spend time assisting researchers around the world with their THz experiments.

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