The Annual Balzan Lecture

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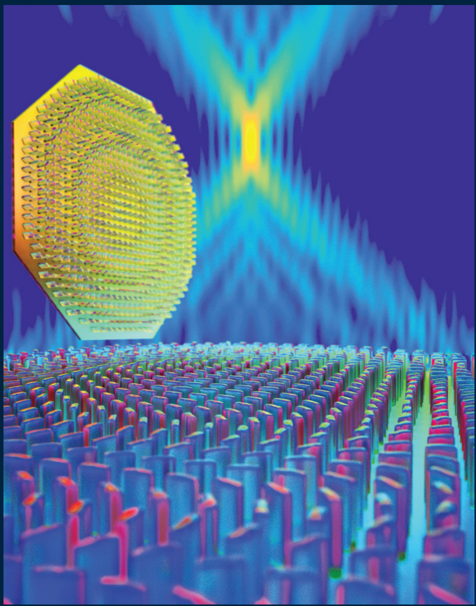
# FROM QUANTUM CASCADE LASERS TO FLAT OPTICS FOR THE TWENTY-FIRST CENTURY

by

Federico Capasso

2016 Balzan Prizewinner



LEO S. OLSCHKI

2019

Federico Capasso

*From Quantum Cascade Lasers to Flat Optics for the Twenty-First Century*

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Accademia Nazionale dei Lincei

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Alberto Quadrio Curzio
Vice President of the International Balzan Foundation "Prize",
President of the Accademia Nazionale dei Lincei,
President of the Joint Commission Balzan-Lincei-Swiss Academies

# FOREWORD

The International Balzan Prize Foundation Annual Balzan Lecture enters its ninth edition in 2018, with a lecture on developments in the field of applied photonics, delivered by Federico Capasso. In my capacity as President of the Joint Commission International Balzan Foundation "Prize", Accademia Nazionale dei Lincei and Association of Swiss Academies, I am deeply honoured to write the Foreword to this ninth lecture by 2016 Balzan Prizewinner Federico Capasso, as it enables me to recall the exceptional achievements of all of our Balzan Prizewinners, as well as to spread knowledge of the Foundation among larger audiences. Once again, we have the opportunity to attend another important event demonstrating the Foundation's long-standing commitment to furthering the sciences and the humanities.

Born of a joint agreement between the Swiss Academies of Arts and Sciences, the Accademia Nazionale dei Lincei and the Balzan Foundation, this distinguished lecture series stands as a testimonial to their constructive collaboration dedicated to creating opportunities for Balzan Prizewinners to present their achievements and share with their audiences the results of their Balzan Research Projects. The Annual Balzan Lecture series also recalls the Foundation's primary aim of fostering communication between the sciences and the humanities at the highest level of international scholarship. This aim is also manifest in another important initiative resulting from collaboration between these institutions: *IinteR-La$^{+}$B*,[1] an interdisciplinary research laboratory

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[1] The first part of the acronym stands for International Interdisciplinary Research Laboratory, while the second combines an L for the Lincei, an a+ for the Swiss Academies and a B for Balzan.

where past Balzan Prizewinners and young researchers involved in the Balzan Research Projects exchange ideas. In short, the Annual Balzan Lecture encourages contemporary academic discourse and exchange in a community of scholars working together on common goals – not only in the subject area of the lecturer, but in all disciplines as well, thus in the interdisciplinary spirit that marks all Balzan endeavours.

The vast gamma of subject areas covered by the Annual Balzan Lecture reflects the interdisciplinary focus of the Balzan mission, as can be seen in the short synopsis that follows. In the first volume, winners of the 2005 Balzan Prize for Population Biology Peter and Rosemary Grant presented the results of their research project involving young academics on the seminal topic of *The Evolution of Darwin's Finches, Mockingbirds and Flies*. In the second lecture, *Humanists with Inky Fingers: The Culture of Correction in Renaissance Europe,* 2002 Balzan Prizewinner for History of the Humanities Anthony Grafton provided a detailed analysis of how the meaning of texts was influenced by correctors during the Renaissance. The third lecture by Colin Renfrew, 2004 Balzan Prize for Prehistoric Archaeology, illustrated the findings from his excavations on the Greek island of Keros in the project *Cognitive Archaeology from Theory to Practice*. Michael Marmot, 2004 Balzan Prize for Epidemiology, delivered the fourth lecture, *Fair Society*, *Healthy Lives*, where the social determinants of health were explored. 2012 Balzan Prizewinner for Solid Earth Sciences Kurt Lambeck's lecture, entitled *Of Moon and Land, Ice and Strand: Sea Level during Glacial Cycles*, contributed to the debate on the consequences of human impact on the Earth as well as to the very long cycles of changes in the world's physical structure. Terence Cave, 2009 Balzan Prize for Literature since 1500, gave the sixth lecture, *'Far other worlds, and other seas': Thinking with Literature in the Twenty-First Century*, with an analysis of selected literary texts and the issues encountered when adopting a cognitive approach to the study of literature. In the seventh Annual Balzan Lecture on *Thinking about Liberty: An Historian's Approach,* 2006 Balzan Prizewinner for Political Thought: History and Theory Quentin Skinner defended a theoretical point of view of liberty based on a "neo-Roman", republican idea of freedom understood as freedom from arbitrary domination by others. In the previous year's volume, *IceCube and the Discovery of High-Energy Cosmic Neutrinos*, Francis Halzen, winner of the 2015 Balzan Prize for Astroparticle Physics, presented the accomplishments which led to the construction of the large IceCube Neutrino Observatory in Antarctica, which has opened up a new view of the Universe through the study of cosmological high-energy neutrinos.

This brings us to today's lecture by Federico Capasso, who won the 2016 Balzan Prize for Applied Photonics. His talk, *From Quantum Cascade Lasers to Flat Optics for the Twenty-First Century*, explores developments in the cutting-edge field of applied photonics, in which he is a key figure, and which has had such a great impact on all of our lives.

## WELCOME AND ACKNOWLEDGEMENTS BY ENRICO DECLEVA

President of the International Balzan Foundation "Prize"

I am very pleased and honoured to extend a few words of welcome by acknowledging the efforts of those who helped with the production of this 2018 Annual Balzan Lecture delivered by Professor Federico Capasso, 2016 Balzan Prize for Applied Photonics. The Prize was awarded to him "for his pioneering work in the quantum design of new materials with specific electronic and optical features, which led to the realization of a fundamentally new class of laser, the Quantum Cascade Laser; for his major contributions in plasmonics and metamaterials at the forefront of photonics science and technology".

First of all, I would like to thank Federico Capasso for accepting the invitation to come from so far away – Massachusetts – to hold this lecture, organized by the Swiss Academies in collaboration with the University of Lugano, the Swiss Federal Institute for Vocational Education and Training, and the Science et Cité Foundation. Finally, I thank the University of Applied Sciences and Arts of Southern Switzerland (SUPSI), our gracious host here at the Auditorium on the Trevano campus in Lugano.

Secondly, this lecture also provides an opportunity to renew my thanks to Professor Alberto Quadrio Curzio, President of the Accademia Nazionale dei Lincei and Vice President of our Foundation, for being the motivating force behind this collaboration between the Balzan Foundation, the Swiss Academies of Arts and Sciences and the Accademia dei Lincei. Such mutual efforts as the Annual Balzan Lecture underline the Italo-Swiss nature of the Balzan Prize and the multidisciplinarity that inspires the lecture as well as all of the other events that the Balzan Foundation organizes to foster experimental sciences and the humanities.

Last but by no means least, I would like to express my gratitude to the President of the Swiss Academies, Maurice Campagna, for proposing the idea for Professor Capasso's lecture, for his help in its organization, and finally for presenting our Prizewinner, Federico Capasso.

## PRESENTATION OF FEDERICO CAPASSO BY MAURICE CAMPAGNA

President of the Board, Swiss Academies of Arts and Sciences

First of all, I would like to say that it is both a great pleasure and an honour for me to be with you here today in Lugano. As an opening, I will show a slide of the Bernese Alps to thank Enrico Decleva, President of the Balzan Foundation "Prize". It is fair to say that, without President Decleva, we would not be here with Federico Capasso tonight, or have this fantastic collaboration that has significantly improved in the last two or three years due to his dedication to strengthening the bond between Northern and Southern Europe, and in particular, the North and South of Switzerland, thus the Bernese Alps that you see here. Enrico Decleva has helped us a great deal by appearing every time we need him in Bern to participate in the various events involving the Balzan Foundation. Again, thank you very much for coming especially from Milan today for this event, Enrico.

Obviously, I have to admit that it is a special feeling for me tonight to have this fantastic occasion to present Federico Capasso, because he started his career in a significant way in a place where I also had the chance to participate. But before that, he had spent some time in a very important place, Enrico Fermi's Scuola di fisica – where the great scientist also worked – in Rome. Capasso had very important teachers, whom we both enjoyed together, like Franco Bassani, who was also very active in Zurich. Or Giovanni Jona-Lasinio, who did not receive the Nobel Prize, but frankly speaking, actually deserved it, together with Yoichiro Nambu. Then Federico also had the chance to study with Francesco de Martini, the professor who spent a lot of time in the United States, and actually brought the idea of quantum optics to Italy. Federico did his PhD with Martini.

It is very interesting for me because in 1976, through a grant from the Rotary Club, Federico managed to join Bell Labs. As a young student just after the PhD, he was so good that he immediately became a member of the Bell Labs staff, and he stayed there for twenty-seven years, as we know, going through all the changes that very often happen in the United States, with restructuring in research and in industry. He was very successful, becoming vice president also of the current Lucent Laboratories in Maryville, New Jersey. I imagine that, like myself in 1972, he entertained the question: "Are you sure that you want to climb the Everest of R&D?", which is what being at Bell Labs was like at the time. On Everest, the wind is very icy and the air is very thin, so to speak, so many of you who know Bell Labs understand very well what I mean. In fact, in the 1970s and 1980s Bell Laboratories was "the cathedral for research". In many ways it still is, because of the major discoveries that have generated everything we use today, namely integrated electronics, starting from the 1947 transistor to something we are going to hear more about today, the laser of 1970, the more classic one based on atoms and molecules, which then basically set the whole technology that we use for optical communications – fibres, amplifiers, speech recognition and so on and so forth – in motion. In the 1970s at Bell Laboratories, when Federico was active there, a very important field of technology was developed: molecular beam epitaxy (MBE). He collaborated very closely with our colleague, Alfred Cho, to develop this technique for integrated electronics using quantum wells, which is the basis for showing that this quantization is very important, also for solids like atoms and molecules. In the 1980s, Federico developed MBE for stair-step heterostructures, which allowed him to discover the quantum cascade laser in 1994, and I am sure we will hear more about the quantum cascade laser from Federico himself today. Now, after these very important discoveries and developments that basically revolutionized the possibility of using lasers, Federico decided to join the world of academia, and went to Harvard. Cambridge, too, is a very special place because in contrast to many European universities and even our own ETH-Rat, whose President is here tonight, there are not necessarily departments, but schools, which makes discussion and interdisciplinary projects simpler and less bureaucratic. In this context, he developed new didactic methods, and here in particular, he had the idea to develop so-called 'flat', or bi-dimensional optical components. In addition, I would say he became a more precise entrepreneur.

Here I will conclude my presentation to make sure that Federico Capasso has enough time to explain everything he has done in his fantastic life, and to answer the question "Who is Federico Capasso really?" In an interview with Claudia Pensella in September 2017, when Federico came to Lugano for the Balzan's annual IinteR-La$^+$B seminar[1] involving the Balzan community of Prizewinners and young researchers carrying out the Prizewinners' research projects, he said, "Well, I am a designer." Federico is a designer of artificial, man-made materials and quantum optical devices. For specialists, this is easy to understand, but for the layman it might seem a little more complicated. I always tend to characterize Federico as a true scientist – a *feu sacré* at all wavelengths, and across the whole spectrum of communication. Federico is a lifelong source of inspiration and a point of reference for his students and colleagues.

We are very happy to have you here with us today, Federico, and it is an honour and a pleasure to listen to your talk. Thank you very much.

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1 The seminar was designed in 2011 by Alberto Quadrio Curzio, Vice President of the International Balzan Foundation "Prize", as a collaborative effort organized by the Balzan Foundation, the Accademia Nazionale dei Lincei and the Swiss Academies of Arts and Sciences. Since its approval in a joint agreement among the three institutions, who host it in alternate years in Italy or Switzerland, it has gone through eight editions.

Lecture by Federico Capasso

## FROM QUANTUM CASCADE LASERS TO FLAT OPTICS FOR THE TWENTY-FIRST CENTURY

I will tell you a little about my scientific adventure, which I have called *From Quantum Cascade Lasers to Flat Optics for the Twenty-First Century*. Science does not happen without people; they are the main ingredient. Of course, you need ideas, but if we professors do not have great students, we basically cannot do anything at all except write proposals, and that in itself is not so exciting. This is my current group (Figure 1). As you can see, they are very energetic, very creative, young people.

Let me take a step back for a moment, to the year 2015, which the UN decided to designate as the International Year of Light and Light-based Technology – why? I started, particularly at Bell Labs, doing solid-state physics, electronics, and then I moved full force into optics, which is a discipline that is like a scientific platform. I challenge you to name a field of science or high-tech that does not use optics in some capacity – even computer technology to connect computers with fiber optic links with light launched by tiny lasers. If you go to CERN, you will see that in order to manage the extremely high data rates, optical interconnects are employed. Light is everywhere. Yet even Einstein said, "You know, I still can't figure out what the photon is," even though he was the one who introduced it with the famous 1905 paper on the photoelectric effect. To return to my initial point about the UN International Year of Light and Light-based Technology, in his speech, the Secretary General of the United Nations Ban-Ki-Moon made it very clear that light technology is truly a crosscutting discipline in the twenty-first century. Let me give you some quick examples (Figure 2).

Light technologies include applications ranging from pollution monitoring to augmented reality and flat optics. There is also the

Fig. 1. Federico Capasso's research group.


Fig. 2. Uses of light technologies.

quantum regime of optical technology, where single quantum emitters placed into diamond are used to do nanoscale magnetic resonance imaging – in vivo functional imaging. This is a very "hot" frontier. Of course, there is also the world of lighting and communication and – why not? – the connection with culture and art.

I arrived in the United States when I was twenty-six years old. I had a Rotary scholarship for nine months, but then interesting things started happening and I ended up staying longer. My career started at Bell Labs and took off when I started to collaborate with Al Cho, the inventor of molecular beam epitaxy (MBE). The technique is simple to explain – to do it is another story. For that, the experimental genius of Al Cho was necessary. Molecular beam epitaxy (MBE) is like spray-painting atoms on a surface (Figure 3). Consider a crystal under ultrahigh vacuum: basically, there are no contaminants. Small super-hot furnaces literally spray atoms of different elements, which could be gallium and arsenic. In the case of gallium arsenide (GaAs) and

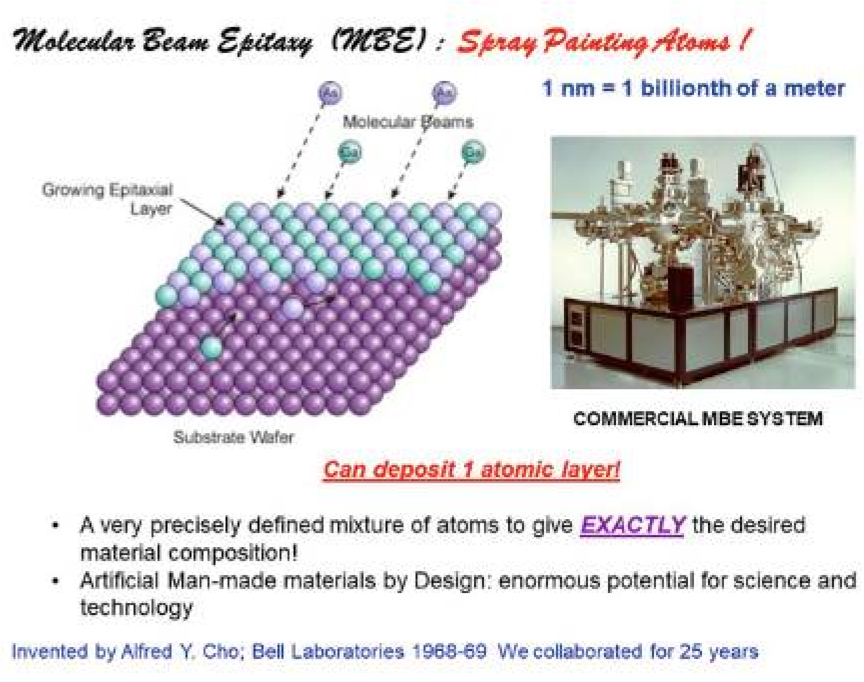



Fig. 3. Molecular beam epitaxy (MBE).

more complicated materials, you can practically do layer by layer – atomic layer by atomic layer growth.

Layers of different materials can be alternated since the thickness is so small – in fact, smaller than the wavelengths of the electrons in the materials. They behave simultaneously like particles and waves. We can say that electrons endow novel nanostructured material with new man-made properties. That is truly the revolutionary aspect: artificial, man-made materials by design have a major impact on science and technology.

As soon as I started to collaborate with Al Cho, I said, "This is going to be endless. This is going to be so much fun." I felt like a kid playing with incredible toys! Although we were just "doing it for fun", this aspect is an important component of scientific research. Today, molecular beam epitaxy MBE is a commercial system, and has contributed to the development of many different devices. For example, one of the most outstanding ones is the world's highest speed transistor. The so-called heterojunction bipolar transistors or ultra-high-speed transistors are made by means of MBE.

To give you one example from my own research, I will explain the **quantum cascade laser** (**QCL**). It is made of multiple layers, the thinnest of which is basically five Angströms. It alternates two different materials. In the illustration (Figure 4), black means one material; white means another. This cross-section is obtained by high-resolution electron microscopy. What happens is that current is injected from the top to the bottom of the structure, and the electrons cascade down the staircase – think of a series of steps. An electron is not just like a sphere, because it can be both a wave and a particle. At every "step", it emits a photon. That's the central idea with this truly beautiful technology that enables us to do so many things, like changing the wavelength of the emitted photon to match almost any molecular fingerprint. By using the same combination of constituent materials, and by changing only the layer thickness, this new laser concept makes it possible to change the laser wavelengths across the entire infrared region. The infrared is a region of invisible light, but it's still very useful, and even dangerous at high power.

That is the key point. With this, we were able to target a region of the spectrum where there were not really many significant lasers until now. The concept is simple – to be honest with you, you almost

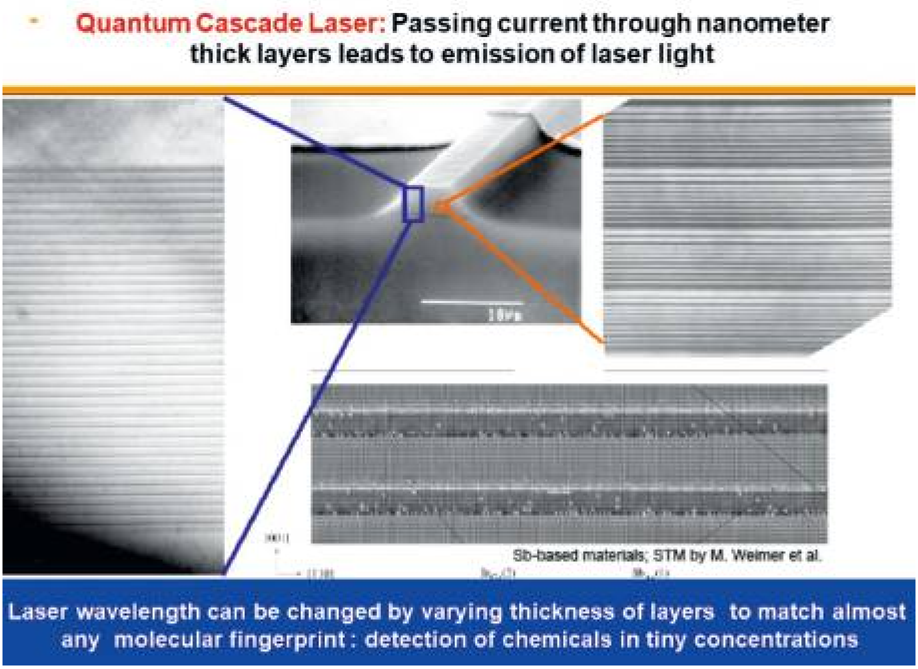



Fig. 4. The quantum cascade laser: matching molecular fingerprints.

do not need to know any physics at all to understand it! I literally create a series of steps and I let the electrons go down the steps. This transforms energy, because when a particle goes down, it rolls down a series of steps and gains energy (Figure 5). Imagine a series of energy steps, separated by distance inside the material. The steps can be engineered in a certain way so that they behave like artificial atoms. These artificial atoms can be made with discrete energy levels.

The energy level difference gives you the energy of the photon, which corresponds to the wavelength. To get this staircase, voltage must be applied to the structure, which allows to inject the electrons and that's the neat physics! It is designed using quantum mechanics, so can be called "quantum design". At every step, a laser photon is emitted. If you have 20 steps, one electron creates 20 laser photons.

Moreover, these materials are semiconductors – materials which all chips are made from, like silicon chips and the like. Semiconductor lasers already exist: those that send light in optical fibers emit in the

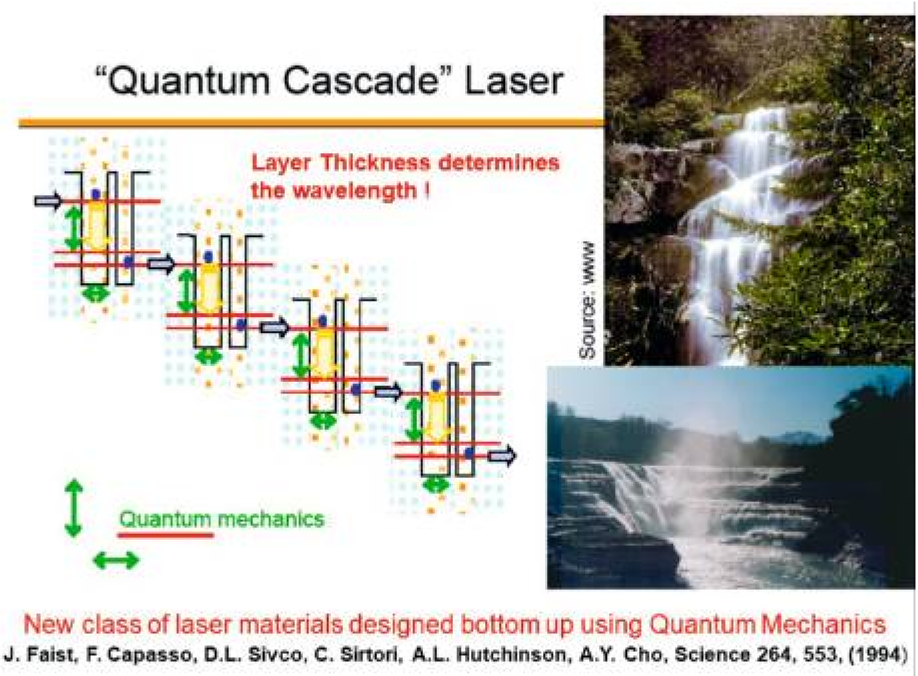



Fig. 5. The quantum cascade laser.

so-called near-infrared light spectrum. These are based on an entirely different principle than the QCL. QCLs are particularly useful for targeting a region of the light spectrum where until now there was essentially no real significant compact and tunable laser. The spectral coverage of lasers is shown in Figure 6. In the visible, you have a great deal of lasers. In the near infrared, you have the famous diode lasers, widely used for communication and many other applications.

In the mid-infrared, there were basically very few good lasers until the QCL was invented. The carbon dioxide ($CO_2$) is a very powerful laser but its wavelength tuning range is small. In the QCL, by engineering the material, we can get the entire wavelength coverage of the infrared from essentially a few microns up to 300 microns – two orders of magnitude of wavelengths. What is more, given a particular laser, we have developed techniques that make it possible to actually tune the wavelengths of a particular laser.

These lasers have found applications in all kinds of areas, for example, the molecular fingerprint region (Figure 7), which has this name because most molecules absorb light in this invisible region of the spectrum. These lasers started to flourish, and now – I cannot count them all any more – there are now probably more than thirty-five companies from large to small.

QCLs are being used for a large number of applications: process control in industry, for the detection of explosives and hazardous gases, for compliance testing and – this is still under development – for breath analysis, which in my opinion is one of the most exciting areas. Finally, there is also atmospheric chemistry, which is more science-related. My atmospheric chemist colleagues point out that these lasers are also changing the nature of our understanding of atmospheric circulation, because fine-grained mapping of greenhouse gases can be achieved, and this can affect the modelling of climate change.

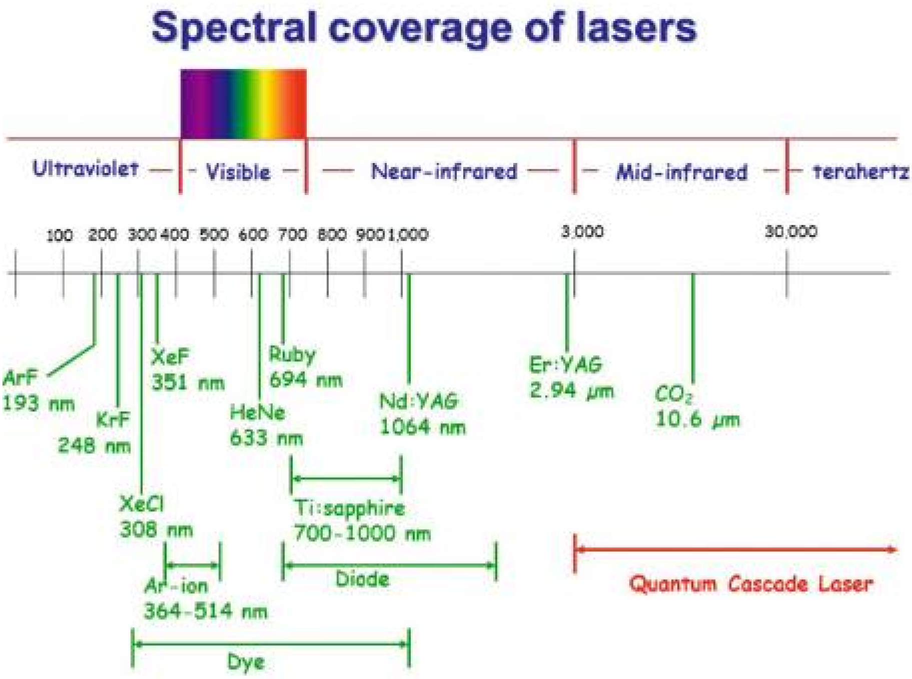



Fig. 6. Spectral coverage of lasers.

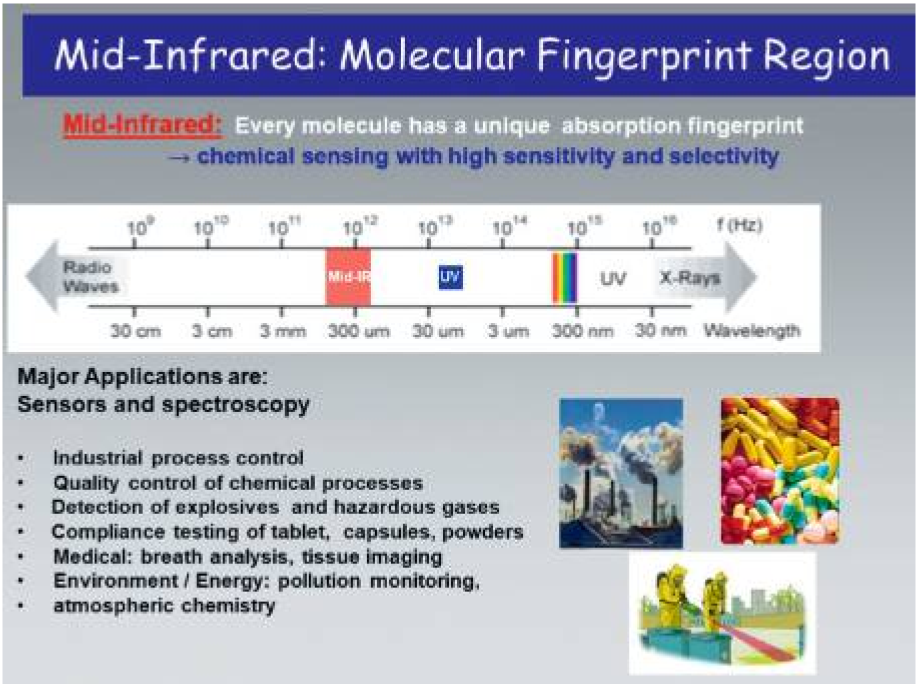



Fig. 7. The molecular fingerprint region.


Fig. 8. Applications of mid-infrared technology.

Other applications that use mid-infrared technology in general are being developed (Figure 8).

To continue on the subject of QCLs, let me give an example of how they can be used (Figure 9). Suppose you want to determine one part in 1 billion ($1{:}10^9$) – no, let me make it even tougher: one part per 1 trillion ($1{:}10^{12}$) – in volume of a chemical. That is such a tiny amount that you must use "tricks".

In this case, the trick is very simple and has been known for many years. It uses a laser coupled to an optical cavity, where you insert the chemical. This is designed so that light bounces in and out, left and right, many times, so that even if the cavity is only maybe about 50 cm long, the effective path can be 70m - 100m. This is important because if there is a tiny amount of a chemical in a single pass, the attenuation is going to be negligible. You want to measure the attenuation of the laser pulse in going through the multi-pass cavity. We can so detect very small amounts of chemicals, indeed down to parts per trillion. I think that our lasers hold the record. The use of the quantum cascade laser QCL has expanded this spectroscopy tremendously.

I will give you another example with the following experiment, which was done by one of my collaborators, Professor Robert Curl, a very famous chemist (Figure 10). He was the co-winner of the Nobel Prize for the discovery of the famous buckyballs, but it turns out that the work leading to this discovery was something he only did on the side! I told him, "If you manage to get a Nobel Prize for something you were doing on the side, that's really impressive." Curl's main activity is spectroscopy, which he used in breath analysis, a technique for determining the amount of ammonia in a person's breath. With this experiment, Curl and his colleagues were able to detect 6 parts per billion in volume of ammonia. This field is developing, so I cannot speak of commercial deployment yet, but I think it will happen soon.

This leads to me to ask a question. How can I make a QCL, which is designed for one wavelength, into a broadband laser using a compact chip, say a couple of millimeters in size? Compactness is important for applications. I want to make sure that it emits not one wavelength, but many wavelengths (Figure 11). This very simple idea was an engineering project that led to my first start-up company.

We decided to make different QCL lasers, each emitting a somewhat different wavelength. Then, using off-the-shelf electronics –

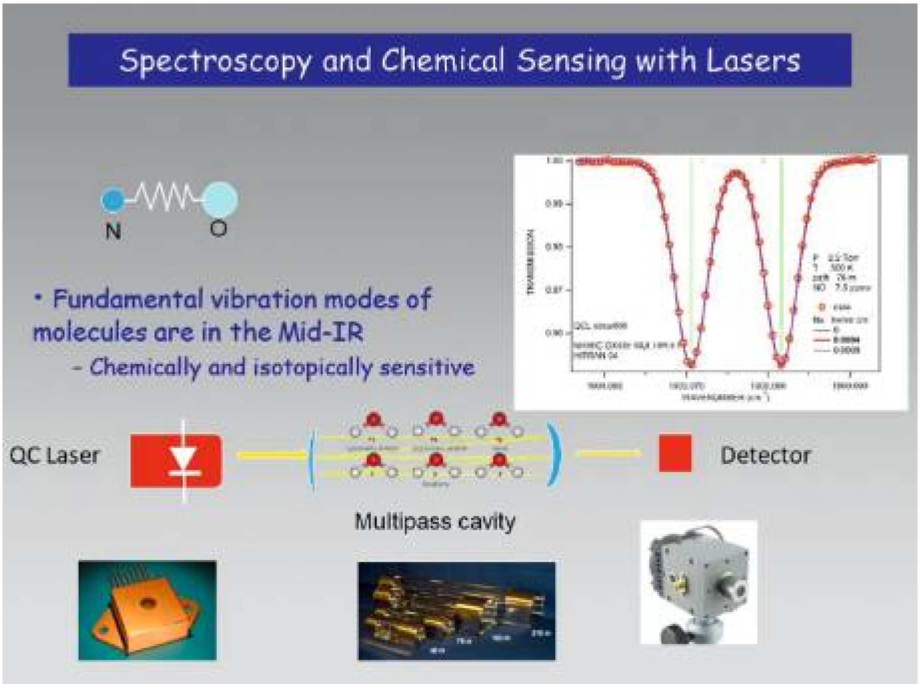



Fig. 9. How the quantum cascade laser is used.

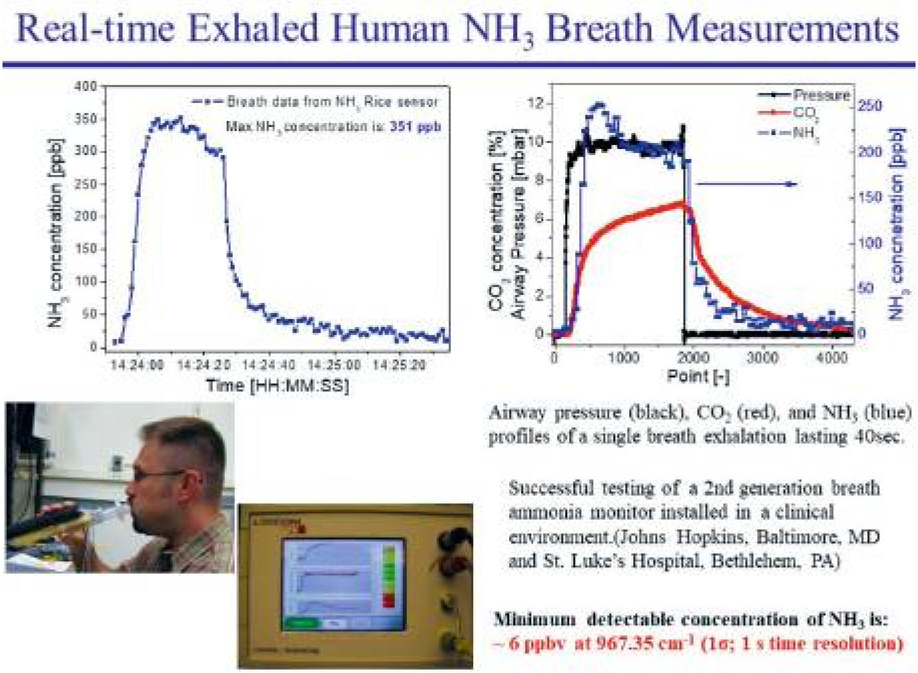



Fig. 10. An experiment in breath analysis.

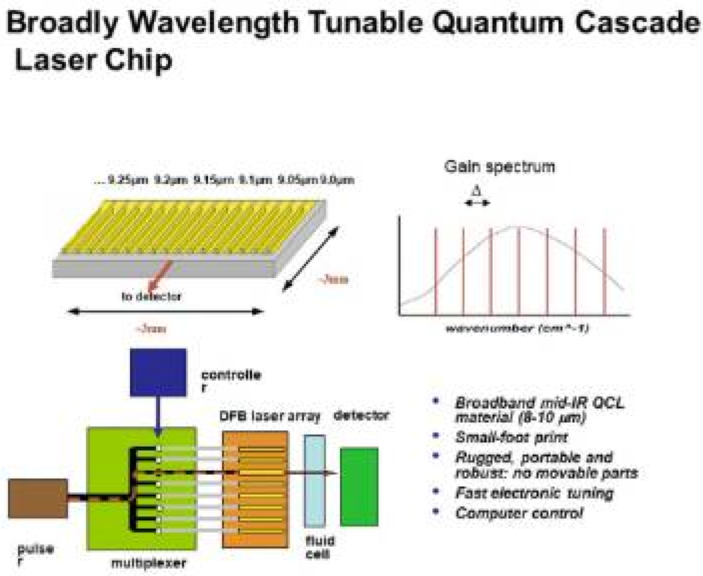



Fig. 11. Broadly wavelength tunable quantum cascade laser chip.

microcontrollers – we could send pulses to each laser in any sequence we wanted, to generate any sequence of wavelengths allowed by the laser. This is a tunable source where the change in wavelength is obtained by firing sequentially the QLS in the array. The actual chip is illustrated here (Figure 12). There are 30 QCLs.

To continue talking about my career, I never started an actual company until I came to Harvard. At a certain point, I said, "Well, let's try." It was so easy to start a company in the United States that I now regret not having started before. As an Italian, I have always been terrorized by bureaucracy; the Italians in this room understand me! Indeed, one of the main reasons I left Italy was because of the endless bureaucracy. Instead, in the USA we did the paperwork in literally one hour, and then we started to talk to venture capitalists. Nothing happened. Two days before the deadline we had set for ourselves for giving up, one of my acquaintances came forward with a donation of half a million dollars. That was enough to start. Then other money came in. Beginnings are always hard.

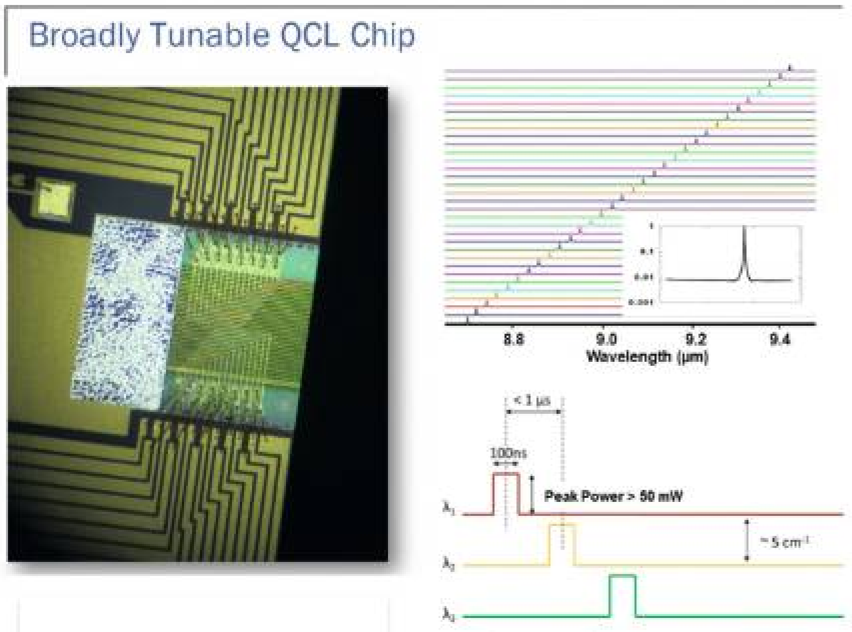



Fig. 12. Broadly tunable QCL chip.

We did pretty well. My co-founders are Mark Witinski, Christian Pfluegl and Laurent Diehl (Figure 13). Diehl, a Swiss citizen, was a student of Professor Jerome Faist, who played a critical role in the actual invention and development of the QCL. Pfluegl is from Vienna, and Witinski, from the US, is in atmospheric chemistry. We formed Eos Photonics, and then a few years later, Daryoosh Vakhshoori, CEO of Pendar Medical, suggested that our two companies merge, and so we became Pendar Technologies. I am board member, a role that has no power, but I am happy with that because it allows me to stay in close touch with research. Let me now give you some examples of how we are bringing to market breakthrough portable analysis and monitoring systems through the fusion of innovative spectroscopy and data science.

Our first product prototype is called the Matchbox. As you can see from the size, it is clearly very, very compact. It is basically the chip that I showed you before, and the goal is to insert it in full sensor systems. One of the applications (Figure 14) looks like a gun, but it is not. Essentially, one of our chips is incorporated in this device so that the chemicals on an actual surface can be analyzed. To do this, you get close to a given surface, turn on your laser, look at the reflected light, and then you can do chemical analysis. There are indications that a large market will develop in this area. This is important because if there are dangerous substances on a surface, it is obviously better not


Fig. 13. The co-founders of Federico Capasso's start-up.


Fig. 14. Applications: the Matchbox (left); security analysis (right).

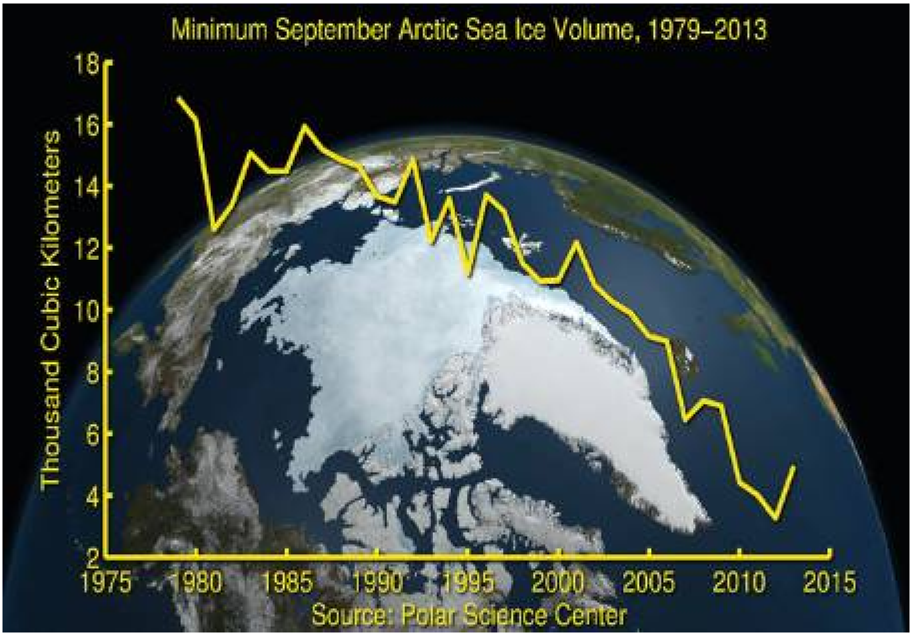



Fig. 15. September Arctic Sea Ice Volume.

to go too close. This is called stand-off detection, because whoever is responsible for doing the detecting can safely analyze harmful substances on surfaces at a distance.

At this point, I would like to switch to the subject of climate change, which is a very serious situation. In fact, I have been working with some of the world's leading atmospheric chemists at Harvard over the last ten years. I do not want to scare anyone, but we have to tell the actual truth – it's more serious than we think. That people still can deny this is just unthinkable. In September, the Arctic Sea Ice Volume reaches its minimum extension. This is how the minimum extension of ice looked in 2010 (Figure 15). Do you know what it was like last year? There was no additional ice in September for a brief period, which is scary. The acceleration has been tremendous, and it is of course the effect of global warming. Global warming is often presented simply as the earth's temperature rising. This is, however, a bit misleading. Why is it misleading? Because the temperature changes look so small that the average person says, "Who cares? You know, a couple of degrees…" The feedback is dramatic because of the greenhouse gases absorbing the heat, i.e. the infrared light. The ice then melts. As it melts, there is less reflectivity. As less light is reflected, everything warms more, creating positive feedback. The process accelerates quite dramatically. There is a problem not only in the North Pole, but also in the South Pole. But there are many cases of feedback like these. One of the colleagues I collaborated with, Professor Steven Wofsy from Harvard, did a magnificent study (Figure 16). He flew QCLs for five years from the South Pole to the North Pole.

He used planes that were formerly used for espionage; one was shot down by the Russians during the Cold War. Now refurbished, this plane is used for science! In any event, in going north, the plane went from the troposphere to the stratosphere (15 km), measuring point by point greenhouse gases like methane, carbon dioxide and other important ones. What is the significance of this study? It is the

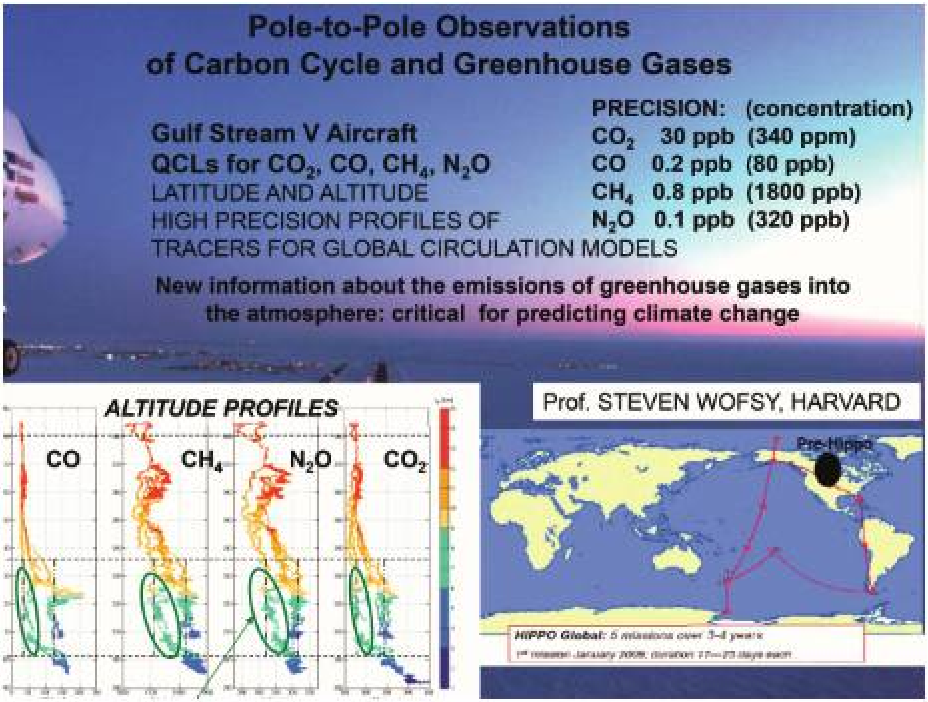


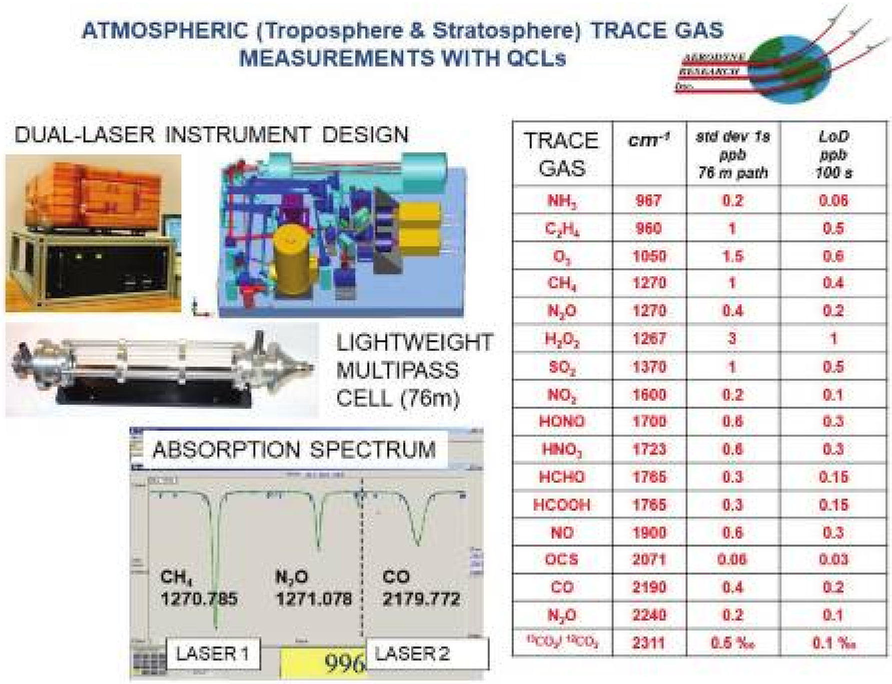

Fig. 16. Steven Wofsy's study on the emission of greenhouse gases.

first fine-grained study of atmospheric chemicals. Fine-grained means measuring the concentration of traces of gases with high spatial resolution, and this was done with a precision down to tens of parts per billion in volume for certain greenhouse gases. These are truly exceptional studies from the standpoint of technique and potential future impact. They provide critical information for establishing reliable models of climate change. This is not my field – I am a provider of lasers, but I love to collaborate with these great people.

This is the system (Figure 17), QCL, which a company called Aerodyne has specialized in making. You can see the multi-pass cell. Light bounces up to a total effective length of 76m, but of course the cavity is much shorter. In this case, there are two lasers in the system, and they can detect three chemicals, methane and two others. The precision can easily be seen (Figure 18). There is a complete set of measurements, which are taken when the plane goes from a very South latitude. This map shows how the locations and strengths of emissions of greenhouse gases change as the plane gains altitude. The color code is an actual concentration of CO and $CO_2$. These patterns provide new information about the location of ground gas emission, and they are the first to provide a high-resolution section of the atmosphere, which is critical for climate modelling.

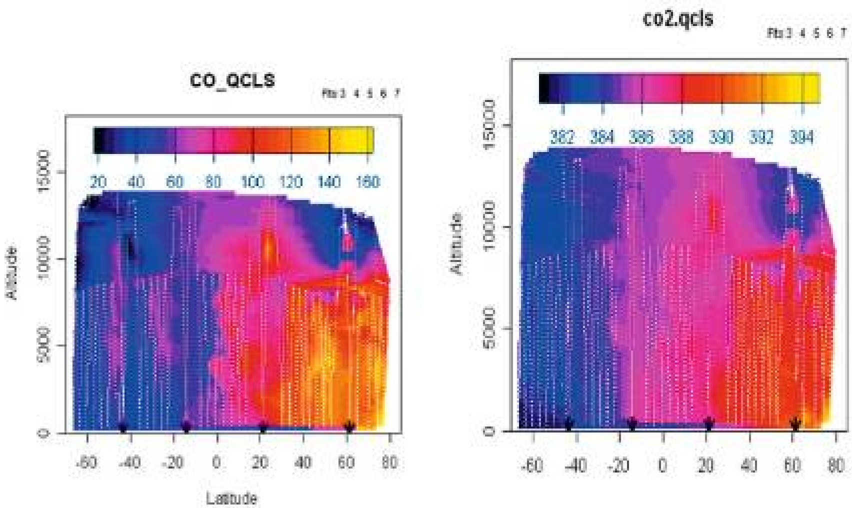
At present, I have another great research interest. **Flat optics** started with a great question from another leading atmospheric chemist, Jim Anderson, one of the creators of the Montréal protocol to control the ozone hole. Instead of flying planes, he loves to fly **drones.** Drones like the one shown here are short, maybe 1m long, so they can reach places in the tundra where normal planes cannot easily go. We have collaborated with Anderson since I was at Bell Labs, by giving him lasers (Figure 19). One day he said, "Federico, I want to send one of my drones very high, to detect high altitude clouds. I want to have one of your lasers, so that when the light bounces I can get chemical information. But there is a problem: I do not want to use lenses."

You might ask why lenses are essential. Lenses are essential because light has to be collimated: laser light still diverges, and quite a bit for QCLs. And a further problem came from the fact that Anderson wanted to have a very direct QCL, but without a lens. I remember saying, "Jim, I think you are crazy, you know, but I will try to think about it." However, "Can you eliminate the lens?" was an incredibly




| TRACE GAS | $cm^{-1}$ | *std dev 1s ppb 76 m path* | *LoD ppb 100 s* |
|---|---|---|---|
| $NH_3$ | 967 | 0.2 | 0.06 |
| $C_2H_4$ | 960 | 1 | 0.5 |
| $O_3$ | 1050 | 1.5 | 0.6 |
| $CH_4$ | 1270 | 1 | 0.4 |
| $N_2O$ | 1270 | 0.4 | 0.2 |
| $H_2O_2$ | 1267 | 3 | 1 |
| $SO_2$ | 1370 | 1 | 0.5 |
| $NO_2$ | 1600 | 0.2 | 0.1 |
| HONO | 1700 | 0.6 | 0.3 |
| $HNO_3$ | 1723 | 0.6 | 0.3 |
| HCHO | 1765 | 0.3 | 0.15 |
| HCOOH | 1765 | 0.3 | 0.15 |
| NO | 1900 | 0.6 | 0.3 |
| OCS | 2071 | 0.06 | 0.03 |
| CO | 2190 | 0.4 | 0.2 |
| $N_2O$ | 2240 | 0.2 | 0.1 |
| $^{13}CO_2/^{12}CO_2$ | 2311 | 0.5 ‰ | 0.1 ‰ |

Fig. 17. Atmospheric trace gas measurements with QCLs.




- The measurements resolve the vertical and horizontal structure of the atmosphere: first to provide a high-resolution section of the atmosphere—the QCL spectrometers are uniquely capable of making this kind of observation.
- The patterns provide new information about the locations and strengths of emissions of greenhouse gases to the atmosphere.

Fig. 18. QCL measurements of greenhouse gases.


Fig. 19. Drones used to control the ozone hole.

good question (Figure 20). If you have a laser, and put the lens in front at the focal distance, light is collimated.

I got together with one of my best students, Nanfang Yu, who is now a professor at Columbia, and was actually responsible for the key idea: patterning a laser facet with a nanoscale structure. We put our brains together and decided to make a "contact lens" for the laser. Without delving into the physics involved in this matter, we patterned it with a small thinning insulator and metal grooves on top. Light goes out and travels along these grooves in a surface wave, and this provides the collimation effect. The light comes out highly collimated, with a divergence of only a few degrees as opposed to 60°. That did the job. Once the experiment was done, we wrote a proposal to NASA, who did not accept it. They did not fund us, so it was never done. Unfortunately, we have to admit to being under the control of the funding agencies. This is a very innovative proposal, and despite this first setback, we still hope to be able to realize it in the future.

However, the most important thing is that this then gave us an idea, and now we can go in a new direction, not just the production of contact lenses. We considered the possibility of making a lens flat. This is our most recent work. Normal lenses work fine, using a curved surface to bend light by a phenomenon known since the sixteenth century, Snell's Law. As in the figure, all lenses suffer from distortion in the way they focus, so the image gets blurred (Figure 21). Moreover, if you try with different wavelengths, even more imprecision results as the colors get focused in different spots, so multiple lenses are stacked to eliminate this effect known as chromatic aberration.

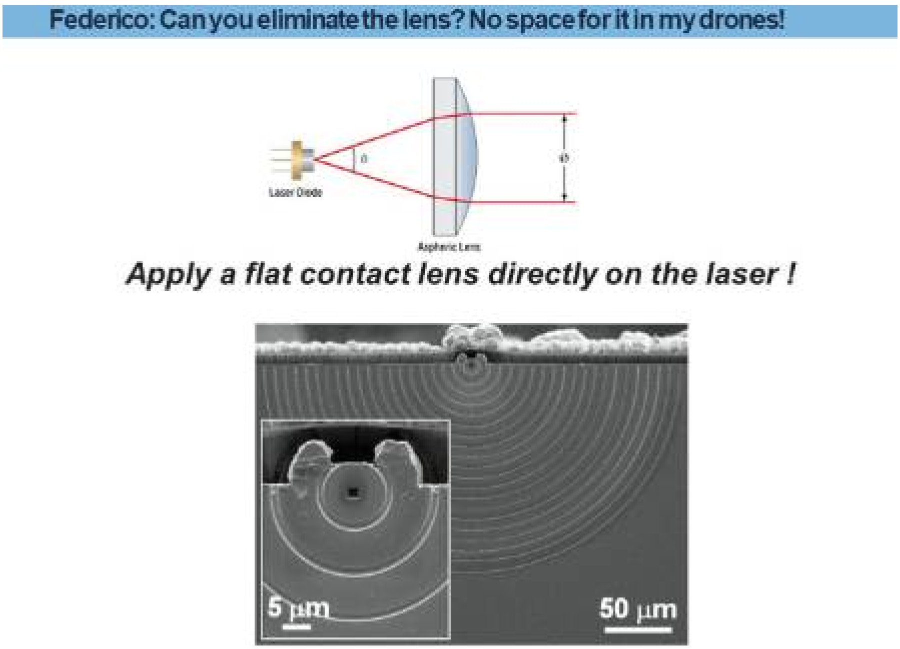



Fig. 20. The problem of eliminating the lens.

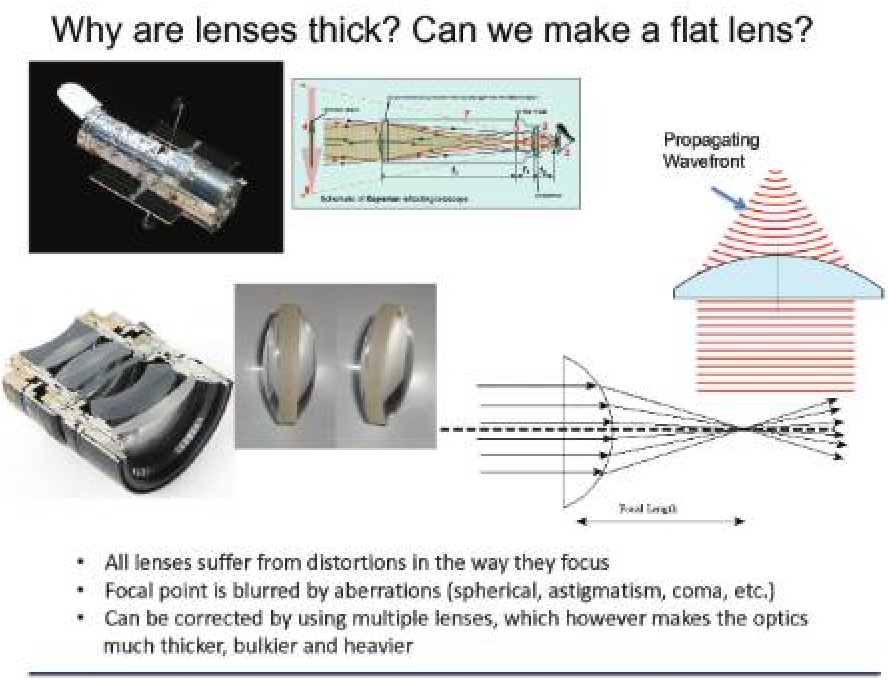



Fig 21. Limits of conventional lenses.


Fig. 22. Conventional lens manufacturing.

Lenses of a reasonable quality are multiple lenses, which are bulky and thick. The technology is so highly perfected that we often forget how elaborate and how expensive it is. For example, in a microscope objective, multiple lenses – as many as ten or even more – correct all the distortions of light in the focus. A special machine is needed just to align them optically (Figure 22).

This machine costs about $1 million. These companies – Zeiss, Leica and so many others – are so good that we tend to forget the complexity involved in lens manufacturing. What if now I could cut nearly flat lenses for various uses? The alignment can be made much more easily. If I can make the lens thinner, then maybe I can correct the aberrations better, and that is not a trivial matter.

Can we make a planar lens? That is the idea (Figure 23); it is a classic example of the use of nanotechnology. The simple idea is to start on the surface, structuring it with a nanoscale feature significantly smaller than the wavelength. That is why I call it planar or flat.

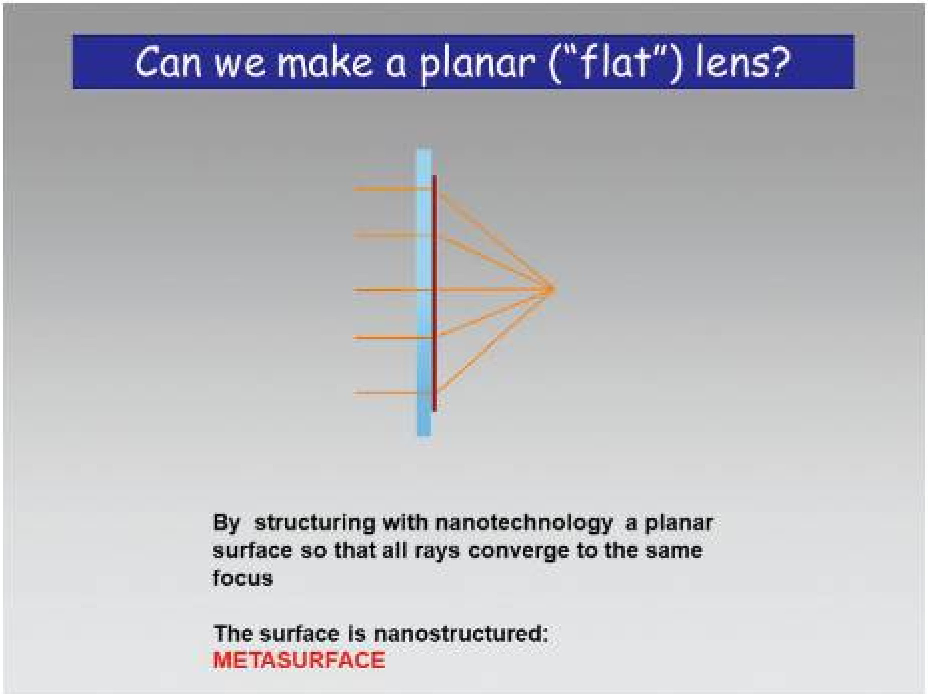



Fig. 23. Using nanotechnology to make a planar lens.

By structuring nanotechnology so that all the rays converge to the same focus, the surface now becomes a metasurface. The idea of how to do this is very simple conceptually. If the lens is flat, I want to make sure that all the rays converge in the focus. This means that the rays must take the same time in going from any point of the lens to the focus. If they arrive at different times, the image is going to be blurred. You may wonder if this is possible because of the difference in the length of the paths; that is where nanotechnology comes in. Light enters, and if the material can be structured so that **light is delayed** differently at different radial distances from the lens center, the total time of arrival from any point of the lens to the focus will be the same. A simple equation can be written and a nanostructure with those capacities can be made. The metasurface that we use is a nanostructure made of titanium dioxide, with pillars that are 600 nanometers tall, and the typical lateral size is to the order of 50 to 60 nm (Figure 24).

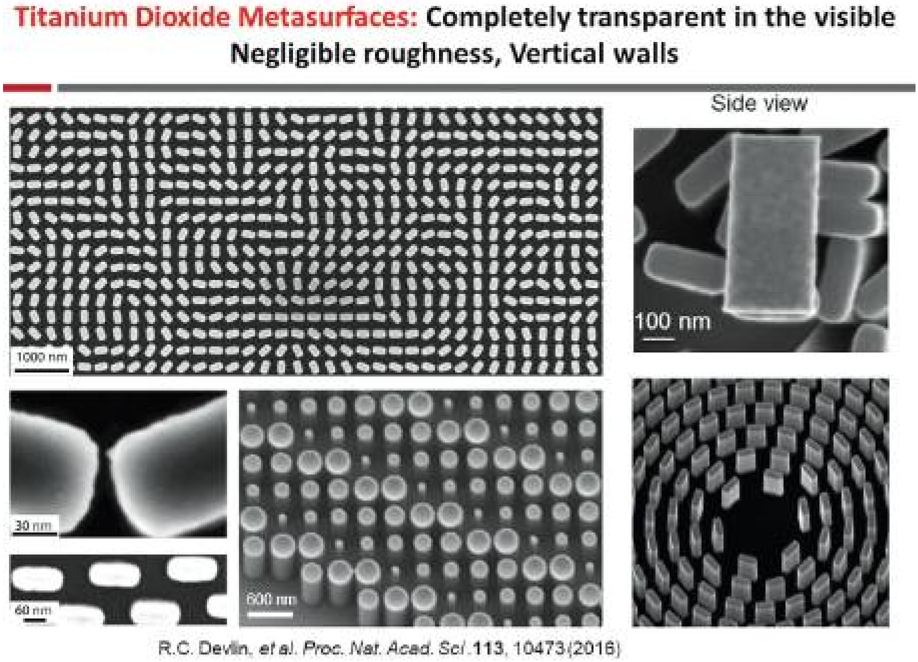



Fig. 24. Titanium dioxide metasurfaces.

The middle micrograph of the lower row is a detail of an actual planar lens (metalens). What is the advantage of this material? It is state-of-the-art, and it has very low optical loss, which means that light is not lost by absorption. Look how perfect these lenses are: they are vertical within one degree, which is very important. Countless things can be done with metasurfaces. For example, what if we do not want to focus light? What if we want to create strange light patterns? Depending on the arrangement of the nanostructure, I can structure light. In fact, today, there is a new field called **structured light**. In this instance, an optical vortex can be created, so that both technology and some fun new science have been created at the same time. This vortex of light is very simple to explain (Figure 25). If I can make light go in a spiral, what happens if I put a camera in front of it?

I will see a vortex of light, which is created with our metasurfaces. This is very exciting. To explain all of this, the spiral results from an interference experiment of the vortex with the original beam.

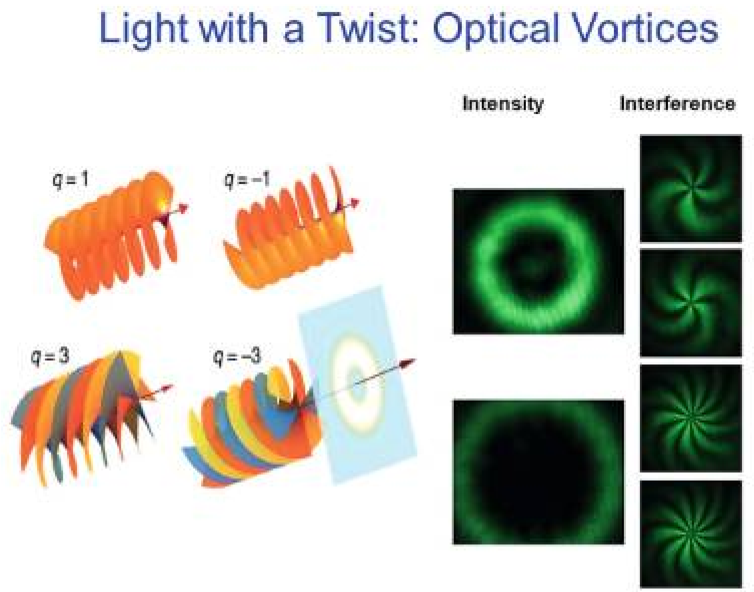



Fig. 25. Optical vortices.

Therefore you have a metasurface, which transforms a regular laser beam into an optical vortex. We have also done much more crazy things! All of this is a lot of fun, but some of it could be useful.

Returning to the lens, in 2016 we published a paper in *Science*, which was the first demonstration of metalenses.[1] The aim was to have the same performance of the state-of-the-art objectives in terms of spatial resolution, which is the ability to see details less than the wavelength, limited by diffraction, as explained in a recent video, "Shrinking Microscope Lenses".[2] This tells the whole story.

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[1] M. Khorasaninejad, W.T. Chen, R.C. Devlin, J. Oh, A.Y. Zhu, F. Capasso, "Metalenses at visible wavelengths: Diffraction-limited focusing and subwavelength resolution imaging," *Science* 352/6290 (3 June 2016): 1190-1194.

[2] Technology is shrinking. Smaller phones, smaller laptops, smaller everything – but shrinking lenses like those found in cameras and microscopes has been a problem. Material scientists are trying to replace glass lenses with something lighter and smaller based on

In a more recent lens, we use cylindrical pillars (Figure 26). In short, two highly reproducible processes were employed. One is atomic layer deposition, which relates to MBE, and the second is a lithographic technique that makes this vertical structure. If you look at the intensity in the focal lens, you will see that these lenses' reproducible processes were designed for optimal wavelengths (Figure 27). As stated in the video script cited above, one challenge is to focus all of the visible light in the same spot.

In this lens, which was designed particularly for the red, we are diffraction-limited when this pattern occurs in the focus. Essentially, the lens sees details as small as half the wavelengths of light. Moreover, they are actually comparable with state-of-the-art objectives. I do not want to claim that we have done better, because these objectives also correct for chromatic aberration. However, the important thing is that they are comparable.

After this discovery, the gates opened. Industrial interest was enormous, and I decided to start a second company. At the beginning of 2018, we reported the first broadband lens. This lens focuses light – all the wavelengths of the visible – in the same spot (Figure 28). We use the same concept as before, but it is more challenging. Every ray enters from the back. In going to a certain point, it must take the same time as any ray going from anywhere on the surface. Now, if you add the constraint, all the wavelengths must do this, so they converge. We made a more sophisticated design, and it works. We

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metasurfaces or engineered materials. In this metasurface lens, tiny towers of titanium dioxide are arranged in a specific pattern to focus light. Different patterns focus different colors of light. In the traditional microscope lens the glass varies in thickness between the middle and edges. Inside the lens, the wavefront of light is shaped via different thicknesses of glass. This focuses the light at one specific point beyond the lens. In the metasurface lens the transparent blocks also bend the light toward the focal point, matching what happens in the glass lens, but with much less material. The tiny metasurface lens building blocks – about 600 nm in length – can achieve the same resolution and magnification as a lens that is 5 or 6 cm in length. Fabrication of these metalenses should also be much more cost-effective, compatible with silicon chip technology versus complex polishing and sometimes stringent requirements for high-performance lenses. The next step is to focus all of the visible spectrum into the same focal length using a metasurface lens. Once this happens, these glitter-sized lenses can replace the lens in a smartphone, regular camera, microscope, or anywhere they may be needed – and the great shrinking can continue."Shrinking Microscope Lenses," accessed 29 November 2018, https://www.youtube.com/watch?v=ETx_fjM5pms.

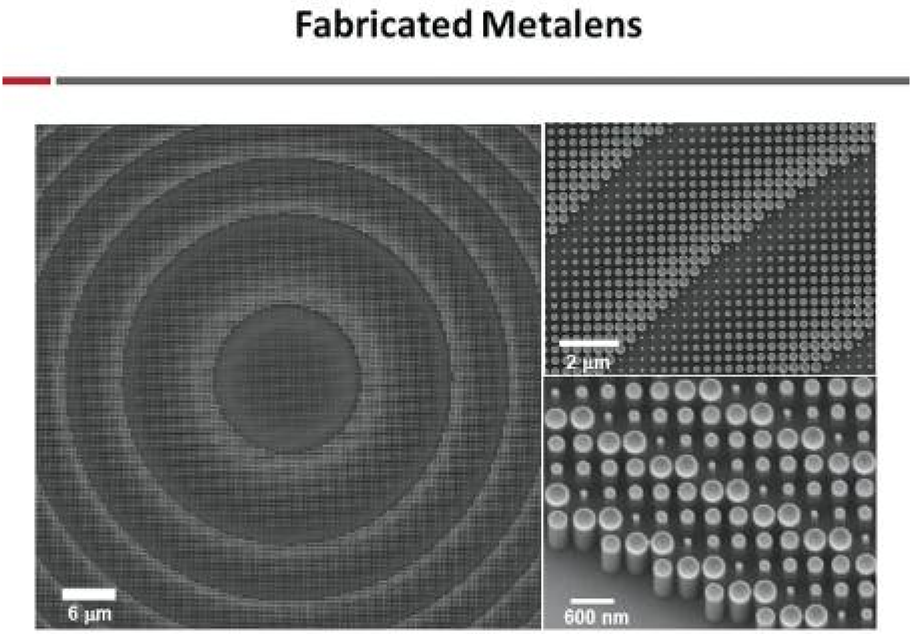


Fig. 26. Fabricated metalens.

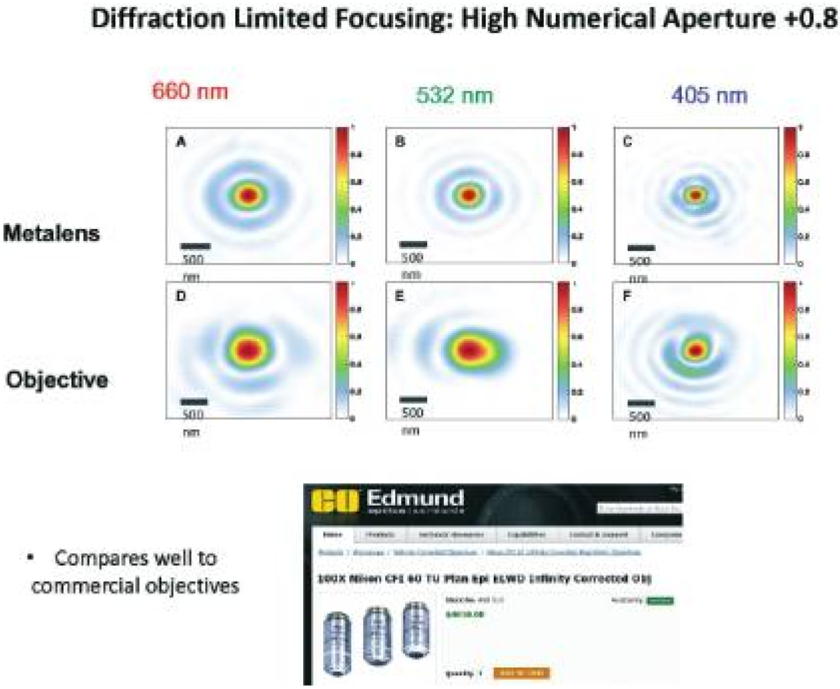


Fig. 27. Diffraction limited focusing.

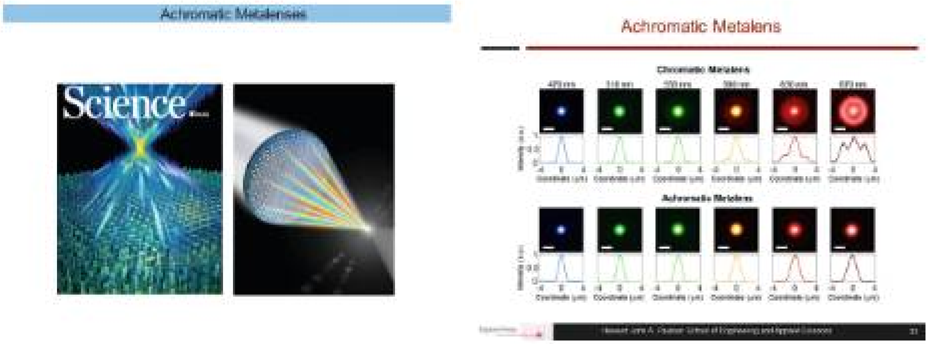


Fig. 28. Comparison of focusing of light of different wavelengths for an achromatic metalens and one with chromatic aberrations.

also published it in *Nature Nanotechnology* at the beginning of 2017. As shown here, if you look at the spot size up to the red, you are essentially wavelength-limited – close to lambda over half in spatial resolution, that is diffraction-limited. If you look at a chromatic metalens instead that does not have the correction for the different colors you see, as you increase the wavelength, the spot size tends to blow up. We can also focus the whole white light spectrum into a single point (Figure 29).

This is very exciting because the most recent development is taking place in collaboration with the Massachusetts General Hospital. Professor Melissa Suter, who leads a group studying lung cancer, approached me with a problem: trying to make bronchoscopes to detect lung cancer optically (Figure 30). There is an optical fiber at the end, with a lens.

Standard spherical ball lenses have spherical aberrations, as do graded index lenses, making it impossible to see any evidence of lung cancer since the spot size is actually strongly distorted and substantially larger than the wavelength. We started to collaborate, and so my students found a way of putting the metalens on the end of a stethoscope. It worked the first time. The images and focal points that you get are much better. This is an example that we can do much better than existing technology. In fact, Suter was thrilled because two days later, she reported being able to detect indications of lung cancer on the scale of a micron (Figure 31). So we are probably going to jointly develop a new class of instruments.

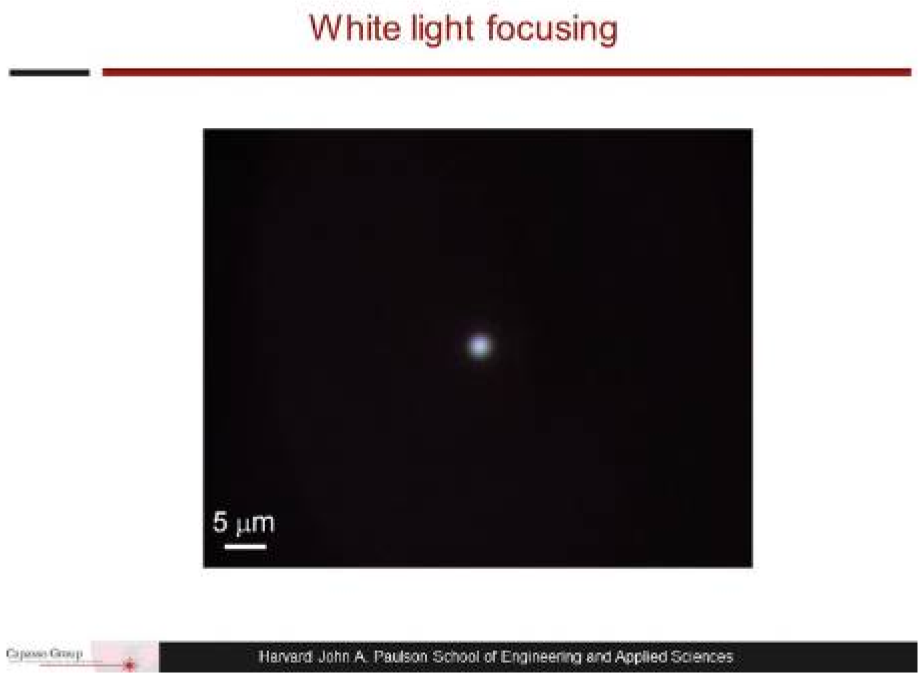


Fig. 29. White light focusing.

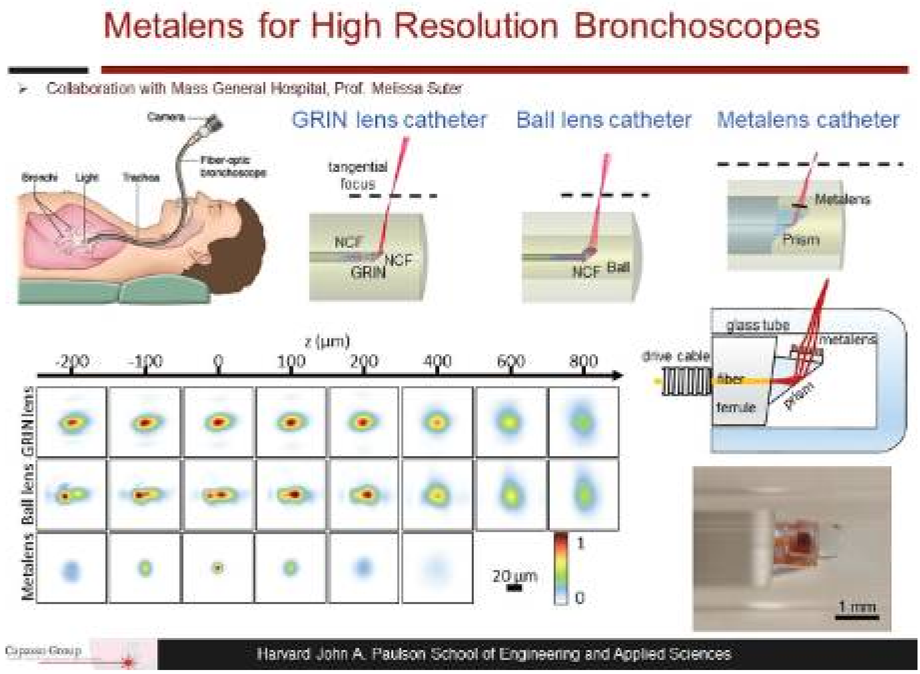


Fig. 30. The metalens employed for high resolution bronchoscopes.

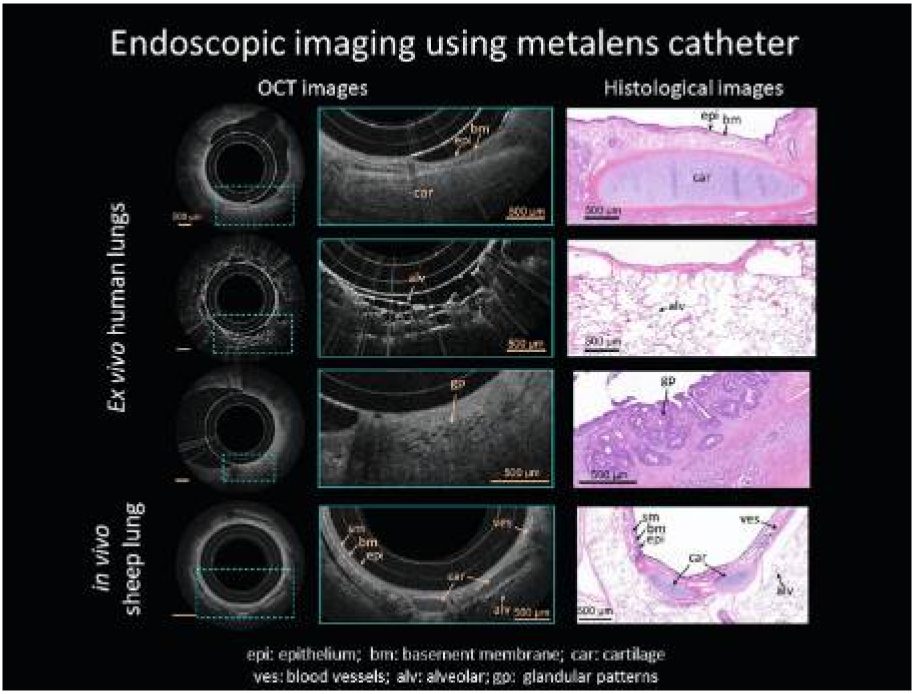


Fig. 31. Other applications of the metalens.

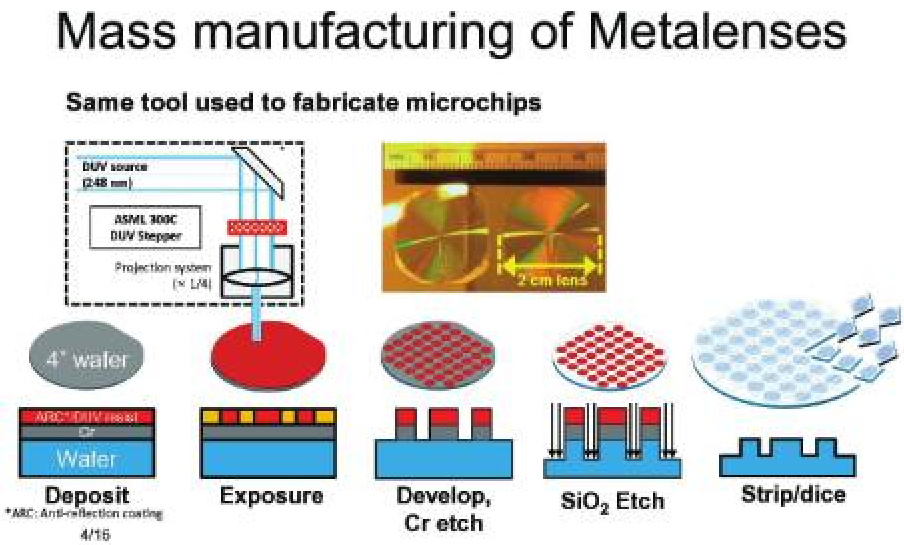


Fig. 32. Fabrication of the metalens.

What is the future of metalens technology? Potentially game changing, because it works in the visible and in the near infrared, and it can be put in all kinds of devices.

Let me give you another example. At present, special companies make the lenses in your cell phone, which are thick and create a bump in the back of your phone. The key point – let me say it again – is that with our metalenses, the camera module and the lenses will be made using the same technology used to make chips. This camera module has a silicon chip which is called a CMOS sensor. Our lenses, just two or three, made by the same company that makes the CMOS chip, will be on top. They will revolutionize the actual business model as they will be manufactured on a large scale and for a small fraction of the cost by the same foundries that mass-produce microprocessors. In fact, one of my students recently went to the Cornell facility, and was able to make a two-centimeter diameter lens – using the same tool used to make integrated circuits (Figure 32), which is quite significant. So the applications are many, and so is their functionality.

We have made lenses that behave like a lens for one wavelength and for another wavelength behave like a totally different device that creates a certain light beam. They can be multi-function, so we started a company with experienced entrepreneurs – Bart Riley, a former student of mine Robert Devlin, and myself. Its name is METALENZ. We have major support from venture capital and – no exaggeration – some of the biggest industries that support us. We are very excited. I think we can truly revolutionize not only the way lenses are made but also the business model. Essentially, lens molding in the long run will actually disappear. Of course, this is my opinion, and has yet to be demonstrated.

To return to the point of optics, two years ago an extraordinary thing happened: the detection of gravitational waves as predicted by Einstein. Scientists realized that they were created by the cosmic union of two black holes spinning round each other, and because of their huge mass, distorting space in the process (Figure 33). What was not emphasized enough – and it is too bad – is that truly extraordinary optical technology made this possible. This will give you an idea of the impact of optics, if you like, in astrophysics. An interferometer was constructed. The interferometer detects changes in length difference between its two arms as small as 1/10000 of a proton's size

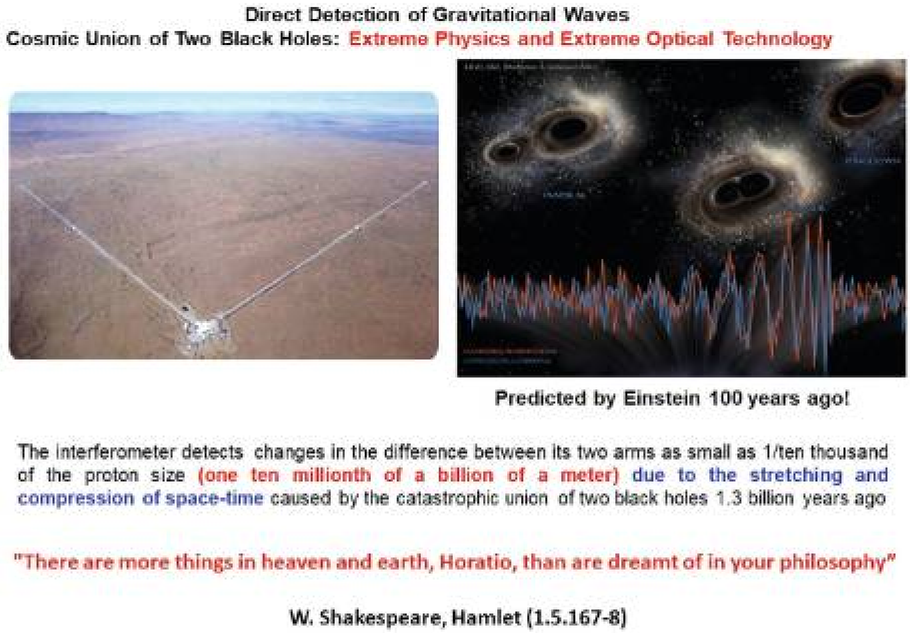


Fig. 33. Direct detection of gravitational waves.

($\sim 10^{-15}$ m), a relativistic effect produced by the gravitational waves that stretch space differently in the two perpendicular arms of the interferometer. This is extraordinary. What you can do now with optics is mind-boggling. This beautiful experiment carries a good lesson: to never separate engineering from physics. They go together. Hopefully, this will lead us to a better society in the foreseeable future.

Thank you very much for your attention.

## DISCUSSION AND QUESTIONS

After the lecture and discussion (from left to right): Swiss Academies of Arts and Sciences President Maurice Campagna, Jean-Pierre Wyss, Jacqueline Mock, Rino Vicini, Luca Schaufelberger, Federico Capasso (centre), Yves Barmaz, Jasmin Allenspach, Karla Lamesic, Head of the Swiss Federal Department of Foreign Affairs Ignazio Cassis (second from right), Michele Dolfi.

This discussion for the ninth edition of the Annual Balzan Lecture focuses on effective ways of meeting the challenge of training the new generation of scientists and researchers working with the innovative technologies applied by Federico Capasso based on the research of his colleagues Prof. Eric Mazur and Dr. Kelly Miller. In the following text, Capasso gives an account of his experimentation with new educational models at the School of Engineering and Applied Science at Harvard

University. The following discussion with Federico Capasso and young Swiss researchers[1] is centred, in particular, on the experience with Active Learning and how to improve learning in the digital age, particularly at the University, as well as on all teaching levels.

*Federico Capasso*: I'm actually a newcomer to the field of new educational methods. About ten years ago, I realized that my way of teaching top down wasn't working too well. At that time, I was teaching graduate courses. I decided to stop just regurgitating what is in an actual textbook. The students do not need a cow that ruminates food – that's not necessary. One day, I decided to restructure my lesson. For the first forty-five minutes in a lecture of ninety minutes, I just give a summary, with the key concepts, not too much math, which the students can get in their textbooks. They don't need me to reproduce ten pages of equations. The rest of the lesson is dedicated to questions, questions, questions. So I start with a question or a simple estimate sometimes – with no data whatsoever – and the students have to figure out the answer. They are divided up into groups of three to five students; I give them three to five minutes, and then I call one out.

The students loved this approach – it was really an eye-opener. And it was just the beginning. For undergraduate courses, I have learned a great deal from Professor Eric Mazur, who is a true pioneer in active learning, and from his colleague Kelly Miller. I've been learning from these new teaching methods, and still I'm far from being an expert. What follows is something like a progress report.

According to Mazur, the traditional model of the top-down, frontal lecture can be described as the "Sage on Stage". But this doesn't work. There is the illusion of learning, but no real learning. Nowadays, there is a great deal of research all over the world on this subject. Another important component in Mazur's method is the participatory

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[1] Four young researchers from two Swiss organizations participated in the discussion with Federico Capasso. From Schweizer Jugend forscht: Jasmin Allenspach (working on a MSc in Physics at ETH Zurich) and Luca Schaufelberger (will begin in the fall of 2019 at ETH Zurich, with interdisciplinary sciences with a focus on chemistry and physics); from Science Olympiad CH: Michele Dolfi (Postdoctoral fellow, PhD Physics, ETH Zurich and IBM Research Zurich) and Jacqueline Mock (Masters student, Interdisciplinary sciences with focus on biology and chemistry, ETH Zurich).

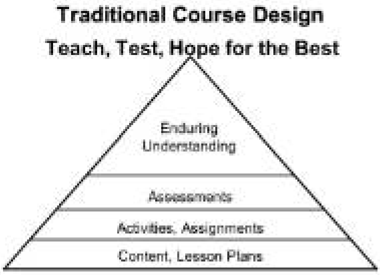

Fig. 1: Traditional Course Design

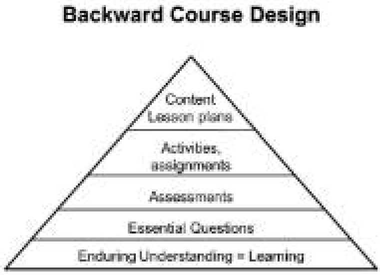

Fig. 2: Backward Course Design

element. While giving a frontal lecture, it seemed that something was missing, so he adopted an alternative approach to conducting a lesson – active learning – which is project- and team-based. The team aspect is important, because the model is participatory – by discussion, by trial and error, you will reach the "scientific truth" more rapidly. You learn by doing. I adopted this method in an applied physics course that I have been teaching with him and others over the past three years. active learning is a tremendous amount of work; it is more difficult than top-down teaching.

As for how this type of course is structured, with the basic course design you start with the lesson plan – content, readings and the like (Figure 1). Then you have to start thinking about problems and assignments. Assessments follow, which might be tests like midterms and finals, or other means of evaluation. Then, sort of like an afterthought, hopefully some understanding and learning will be developed. But will it be developed? That's the hard question, as the saying goes: "Teach, test and hope for the best". This model really must be inverted, and for me it has been a tremendous personal challenge.

This is how an active learning course should be structured (Figure 2). The inverted model starts with the fundamental question, "What do the students really need to learn? At what level? What does understanding mean?" Understanding is not enough. It is only a first step. Learning means your understanding must remain over time – after next week, after a year. Understanding means learning by doing and applying to problem solving.

Other questions must be addressed and focused on before arriving at assessment. However, by assessment, I do not just mean grades. In the US and Europe, not to speak of the rest of the world, there is a kind of obsession with grades: students are assessed simply by being given a grade and a rank. Yet research shows that students who get the best grades often do not get very far in the world of research, whereas others who did not get the highest grades (I'm not talking about the extreme example of Einstein, by the way) could still do very well in research teams. Sometimes all this obsession with grades kills creativity and creates fear.

After assessment come activities and assignments, and based on this we create the lesson plan. After three years of fine-tuning, I can say that this model works, and I'm going to continue with it.

I was attracted by the pioneer of active learning methods, Professor Eric Mazur. With this concept of project- and team-based learning, we always stay on the ground – we stand up, are constantly working with students, we ask questions… In some senses, it's chaotic. But it's good chaos – things happen. Basically, the approach is formative as opposed to outcome focused (Figure 3). Too much of traditional teaching gravitates around the outcome – obsession with grading of students, organizing beautiful lectures. One might give a perfectly clear lecture, but the students might not get it – not because they're stupid, but because the lecture is not the most effective means of communication. With active learning, we reverse the roles. The students study the textbook in advance, and through a platform (www.perusall.com) developed by Eric Mazur, the students find the text online, and can annotate it with their questions. Then there is a chat room for discussion of their questions. You might wonder if they really do check into the system. The system allows us to check on them. In the last session's class of 65-95 students, we counted over 20,000 annotations on the readings.

The next activity is called learning catalytics, which is very innovative. Students go online, and we deliver a question to their laptops. They have about one minute to enter their answers individually. We look on Instagram for the replies. Then a discussion phase follows, and the students rapidly converge on the correct answer. Thus, they are learning through discussion – the Socratic method in action! At the end of the chat session, we explain the correct answer, supplementing it with a simple in-class experiment, which is very illuminating.

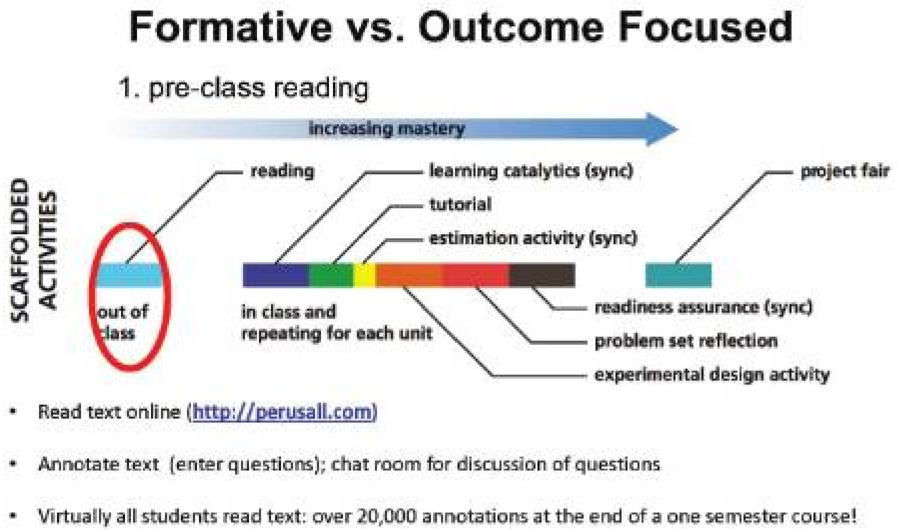


Fig. 3: Formative vs. outcome focused learning.

There is the tutorial, where we deliver qualitative questions, and the students work through them in real time. The instructor and teaching staff (Teaching Assistants, or TAs for short) circulate among students as they work, and we are constantly being bombarded by questions. It's not easy. You become very humble when you teach this way. There's always something you might not understand, even with the most elementary concepts of physics. I'm often nervous, because I know I can make some mistakes, but I can't afford to make too many! I have to be fast on my feet, because I am constantly being bombarded by questions. But it's a good battle.

Another phase is the estimation activities, which recall Enrico Fermi and his famous 'Fermi Questions', for example: "Estimate the number of piano tuners in the city of Chicago" or "What makes the sky blue?" A high level of conjecture is involved. We give the students questions like this, with no input data – and they have to figure out the answer! It's a methodological tool for learning how to estimate things, and it's tremendous fun. I try to create new questions, for example: estimate the pressure in a bottle of champagne – with no other data! There are five or six steps to get to the answer, which turns out to be about four atmospheres.

The next phase: real problem sets. Problems are delivered to the students on the day prior to the class. In class they discuss the solutions, but they must annotate with a red pen so that we can tell what their input was and how they learned by discussion. Another type is the readiness assurance test, which is a synchronized in-class test, the closest to a real exam, but we don't put too much emphasis on the grades, though we give them. The most exciting thing is that in the end, we have a project-based method. We learn by doing, and there is a lot of doing here!

This phase is organized around three projects. The first, for example, to create an electrostatic machine. We give them a short memo, and they have to figure it out. The TAs help by giving demonstrations. The next project is more fun: make an unbreakable safe. The successful project will make a safe that most of the other students can't break. However, many of them are smart; they can break even challenging safes. The third project is a spectrometer to identify a chemical. The projects are demonstrated and judged in a "science fair" by a panel of colleagues.

At this point, I would like to introduce an important question: how does *feeling-of-learning* correlate with *actual learning* for physics majors? My colleagues Kelly Miller, Louis Deslauriers and Logan McCarty in the Department of Physics in the Harvard School of Engineering have written a major but still unpublished paper on this. A sample group of students takes a test: first a conventional, top-down class of thirty minutes and then a different class, which is participatory, on the same subject. Then this process is inverted: first the active, then the passive. Then they are asked which modes leave them with the feeling of learning more. Most of the participants respond that the traditional lecture leaves them with a feeling of learning more, which may come as no surprise. But the stunning thing is the anti-correlation: in quantitative tests of the material presented in both modes (and this has been shown in test after test), the same students who said they felt they learned more with the traditional lecture mode actually got significantly better results in testing from the participatory, active learning class. You may ask why this anti-correlation exists. When you hear a well-delivered lecture, you have an illusion of understanding everything. However, the real learning comes about when you struggle, and when you struggle in active learning, it's messy. You make mistakes; it might be noisy; you have to interact with other people. You don't have this beautiful clarity coming through the words of a great professor, which only makes you *think* you're learning. But you are actually not learning very much.

I will conclude with some personal reflections, based on my experience – a Decalogue of sorts:

- Active learning goes back to the Socratic method: it greatly reduces the barriers between the teacher and the student.
- "All authority is a hindrance, and it is essential that the educator should not become an authority for the student." – J. Krishnamurti.
- Beware of professors – particularly successful ones – who say, "I want my best students to become professors" (meaning following in my footsteps), creating a situation akin to the "imprinting" of Konrad Lorenz's famous theory on the behaviour of migratory birds. In a world that abounds with exciting and fundamentally difficult problems to solve – energy, climate – this "imprinting" or "cloning" is a very limiting view.
- At Bell Labs, I remember that the seminar format was fantastic. Even very famous people in the field would get very hard questions, so I would go so far as to say that we should communicate to students a sort of "healthy disrespect" for authorities in our field. By this I do not mean throwing rotten tomatoes at professors or anything like that, but cultivating a desire for testing, scepticism and critical thinking.
- The barriers between disciplines are gradually crumbling. Here Harvard is ahead, with the creation of entirely new departments like Systems Biology, where biologists work with physicists. It's very exciting. A new synthesis and probably a Renaissance is needed, but we cannot have the Renaissance scientist of the old days. It's impossible to master all of that knowledge nowadays, but we can take steps in that direction if we work interactively.
- The university must change, too. It is still the nineteenth-century German model. Disciplines are convenient, useful constructs

to organize knowledge, but nature does not know what physics, chemistry or biology are.
- Therefore, teaching should be focused more on problem solving than on disciplines: active learning is ideally suited for this. When students build a machine, they integrate knowledge from different areas. They work with their hands, so they're fully engaged in engineering and design.
- In this way, through active learning, we will train people more capable of tackling big societal changes. Geniuses are not simply born that way – creativity can be learned. The most important thing is systematic learning, working together with passion and curiosity.
- Finally, I might add the importance of error. It's unavoidable. I would even say that it's NECESSARY for learning. And with this, I'll open the discussion to see what the students have to say!

*Dimitri Loringett (Moderator)*: Federico Capasso, do we see any future professors in your lab?

*Federico Capasso*: We have to be open with jobs. I always tell students that there are exciting jobs in industry, in academia, in government, in start-ups – go wherever the opportunities are.

*Dimitri Loringett*: A question for the young researchers: after listening to Professor Capasso's reflections on active learning and new educational models, have any of you ever experienced anything like this in your current studies? I'm asking because you all study in Switzerland, and active learning is more in America.

*Jasmin Allenspach*: Switzerland is not as developed in this direction so far. I haven't really experienced it myself. There are some approaches at ETH which are being implemented at the moment, but generally it's good old blackboard and chalk, with a professor standing in front, and 300 students listening. At the beginning of the term, different classes are put together, then as the term progresses, the different courses split up.

I actually experienced more experimentation and innovation when I was teaching. I'm a TA for undergrads, in Complex Analysis. In my classes, I'm actually trying to do something similar. I still teach at the blackboard, in the standard way, but I also actively encourage the students to ask questions all the time. I do that from the very first lecture, telling them at the beginning to ask questions, because the course is for them – not for me! I already know what I'm teaching. Surprisingly, it works. ETH is not that famous for students asking questions, but they do, and I can see that they really benefit from it. I constantly get great feedback from them, so it does tie in somewhat with Professor Capasso's approach. I really enjoy doing it.

*Dimitri Loringett*: Would you ask Professor Capasso for any advice? Are you looking for a career in teaching?

*Jasmin Allenspach*: Well, I thought about that sort of career. I couldn't really see myself as a teacher for my whole life, but certainly for a short period of time. I certainly envision myself more as teaching on a university rather than high school level. But that's still a long way off.

*Dimitri Loringett*: The numbers – I want to ask Professor Capasso about this. active learning is nice, but when you have 300 students in your class, isn't there a risk that it could get out of hand?

*Federico Capasso*: Yes. At Harvard, the typical size where active learning is done is in Physics 15, which has up to 150 students. It can still be done, but not at the right level of granularity. We limit our classes, using a process of application because we want to create a very diverse class in every sense. We have applicants who want to go to medical school, and others coming from liberal arts – they are not necessarily interested in doing a science career. This year we have actually limited the number of participants to 75 because with numbers as high as 95, the method was stretched to the limit. Constant engagement is what's important. I've seen classes with enrollment up to 100, so I'm not saying you can't do active learning with more than 95. What I am saying is that with 250 or more students, you could only introduce some of the elements of active learning. In the future, we'll have to see more of this. Maybe one part of the lesson could be top-down, where essentials are explained, and then you could have more activity on the floor. This way, you could have larger classes.

*Dimitri Loringett*: Let's hear a student's point of view. Luca Schaufelberger, do you ask questions when you're in class? Based on what you've heard in Professor Capasso's talk, would you be more willing to raise your hand with a difficult question and put your professor on the spot? Even though in the ETH it's not done…

*Luca Schaufelberger*: Yes, it's not in the ETH spirit – yet. I think this "healthy disrespect" is really important. To go back to what we were discussing before, perhaps I could mention some special learning experiences we had in high school. In my special mathematics and biology courses, there was one teacher for eight students, so there we could really work in small groups. Concepts were explained on a very simple basis. In the last few years, in tutoring my colleagues, I could really learn something. I agree with Jasmin Allenspach: in high school, it's very difficult to teach the natural sciences and spark interest among young people. Maybe the concepts behind active learning could also be applied to high schools as well as universities.

*Federico Capasso*: Yes, absolutely.

*Dimitri Loringett*: Is there also a problem with high schools in Switzerland? In classes of 20 to 30, surely someone must be curious?

*Jasmin Allenspach*: I agree. It's very difficult to teach STEM subjects in high school. In my opinion, the most interesting physics can really only be done on a university level. For instance, I'm interested in theoretical physics, and that can only be done at university. It's impossible to teach it at a high school level even though interesting things can be done. We're talking about digitalization. I did not really have an interesting physics teacher in high school, but I did view a lot of YouTube channels promoting STEM subjects. I really enjoyed them, and here I am studying physics! The important thing is to raise interest. You can incorporate these sorts of media in lessons. In high school, you can't really do all the fine details of physics, but you can try to raise interest among the students, and YouTube videos are a great way to do that.

*Dimitri Loringett*: So this has nothing to do with The Big Bang Theory?

*Jasmin Allenspach*: No, no…

*Michele Dolfi*: Actually, that's something we managed to propose in the Physics Olympiads. Maybe you know the Veritasium channel. Two years ago, we managed to bring a famous YouTuber (Erik Mueller) to an audience of 450 students. I think that kind of approach is really important to motivate high school students. You have to go outside the class – you cannot package everything that might be interesting inside the classroom. You can profit from people going out, taking videos, and posting problems. Then you can analyse the problems in class. You can try to understand why an object is falling in a certain way instead of another. The videos are good for posing the problem – maybe they should not show the solution.

*Dimitri Loringett*: This leads me to ask about another related topic. There are YouTube videos, of course, but there is also something more structured: what do you think about MOOCs (massive online open courses)? Jacqueline Mock, are you familiar with this form of teaching and learning? Or at least introductory learning?

*Jacqueline Mock*: We had one lecture in my Masters programme, where we were encouraged to watch a certain channel on YouTube. It helped to see different perspectives apart from what our professor was teaching us.

*Dimitri Loringett*: Yes, I understand your search for different viewpoints. But from a digital perspective, like Jasmin Allenspach said, what "clicked" for her as a high school student not particularly interested in physics was watching videos. Could the MOOC be another way to have this "click" happen – to get high school students interested in the pure sciences? Maybe the digital format will help.

*Jacqueline Mock*: Definitely yes, I think one of the advantages is that with YouTube, there are always a lot of alternatives on the right column of the page, so if you're not so interested in the video you first intended to watch, your interest might be attracted by something amazing that pops up on the right! So you start clicking…

*Dimitri Loringett*: Let me ask this question: here and now, if Professor Capasso were to engage in an introductory physics course online, you would definitely sign up immediately, right?

*Michele Dolfi*: Actually, I think this is against what Professor Capasso is trying to do! You definitely lose personal interaction.

*Federico Capasso*: Yes. Let me comment on this. I have asked my colleague and friend Eric Mazur, "Why don't we make the course available online?" He advised me, however, that statistics show that a lot of these online courses have an enormous drop-out rate. There is a famous university – I won't mention its name – which had 200,000 signed up for such courses, but only 1,000 finished.

This happens because there is no social interaction, no community that forms there. You have to set up really effective chat rooms to have some kind of interaction. If you are part of a group, the drop-out rate goes down dramatically. We see that in our model of active learning. The strugglers – the ones that are slow – eventually near the middle or the end of the course come up to speed because there is a support group. The class works in teams on three projects. It's possible to do this online, but I don't think it's been developed at the rate that it should or could be.

*Dimitri Loringett*: At this point, I'd like to address the question, "What is digitization?" Nobody really knows exactly. MOOC is definitely an opportunity. We have actually launched several MOOCs at USI. You're right, Federico, the drop-out rates are huge, but among the many people who sign up – you never know – eventually somebody might come to do courses in the classroom. Classroom interaction is important. Luca Schaufelberger, do you think personal interaction is important? Do you see opportunity with the MOOC in the sense of its leading to involvement in the classroom?

*Luca Schaufelberger*: I really believe that social interaction between the teacher and the student is important, so in that respect I agree with you. But on the other hand, with the MOOCs, we can really optimize the physical place at the university, making it more of an exchange platform rather than a place to just hold lectures. If we have this relation of one lecturer to 300 students, then the social interaction is also not present. By incorporating these MOOCs more into the structure of studying and focusing the university more on this active learning in groups with smaller ratios and pro-check based, we can also bring together start-ups, experts in the field and interested students. I really see a chance here.

*Michele Dolfi*: And maybe there is the link with what Professor Capasso was saying earlier about having the students prepare beforehand by reading their textbooks. Maybe they could attend the MOOC before they come to the class with questions.

I have a question for Professor Capasso: when you create these active groups, what's the size of these groups and how often do the students actually team up in the same groups? Do you force them to mix?

*Federico Capasso*: If we have 70 students, we divide them up into groups of five, and they do the work leading to the first project together. Then when the second project starts, we have entirely different teams, where they're mixed up. So they aren't always in the same groups. It creates a little more chaos, but it works. There's more movement. It's absolutely essential.

*Jacqueline Mock*: I actually have a question related to this. One of the dangers of these massive online tools is that you might get lost – you might start out researching one subject and end up researching something entirely different. In your active learning projects, do you also engage in developing certain research questions, or do you give them guidelines on which path to follow?

*Federico Capasso*: The first step is annotation. The students know we are going to do our in-class discussion on a particular chapter on a certain day, and we give them a week to study it thoroughly. They have to go online – we don't distribute books – and start asking questions to each other in a chat room, where they annotate their reading. That's learning already! In the end, a "Confusion Report" is created, which I read. Out of that report, often some great questions come up. For instance, once after we'd finished the law of refraction and reflection of light, which you can simply derive with a mathematical equation, a student said, "I need a deeper understanding". Great! So we went on with Fermat's principle of minimum time and the propagation of light. I explained with graphics, and they just loved it. The Confusion Report is important. It's not exactly top-down, because we sketch out the answer on the iPad. There is interaction; it is horizontal at every level of the course. There is assessment that the students have to do on their own, but in class, they have a red pen to make marks, and they must observe the honour code, which is quite serious in the United States. After all this, they can actually see how much they have learned by the red marks they make after their initial annotations. This is the most fun part, because they do things; they demonstrate things.

*Dimitri Loringett*: We're coming to end of our discussion. Jasmin, if you were to speak or send something to our Federal Councillor, what would you ask of him in terms of teaching and learning?

*Jasmin Allenspach*: I would mainly talk about teaching in high school. There's a lot to be done there. High school is the place where you really raise people's interest in subjects. I would recommend making education more interactive, including YouTube and things of that sort. You can wait until you get to university for the really hard science, but you certainly need to be motivated for that, and the motivation comes from high school. On a different note, I would definitely try to include everybody. When it comes to university, there aren't that many women. Women are definitely lacking in STEM subjects, which go hand-in-hand with digitalization. This topic is very close to my heart. I experience it every day – there aren't that many women in physics. I fear that women will be left behind in digitalization as well. I would definitely ask him about how to remedy that.

*Dimitri Loringett*: Luca?

*Luca Schaufelberger*: We've talked mostly about high school and university, but we could also talk about how we should also integrate digitalization in the primary schools. To understand the developments that occur now and that will occur in the next twenty years, you have to have critical thinking. I think that IT programming languages should be taught already at an early age. This does not exclude personal interaction – what is most important is to emphasize critical thinking in the Swiss educational system. Still something is missing. As far as digitalization is concerned, we have a very consumer-close approach to the new product. We do not understand the bottom-up mentality, and this could be changed in our education system already at an early age, that is, middle school or before.

*Dimitri Loringett*: Your turn, Michele Dolfi.

*Michele Dolfi*: To bring in more input as far as changing the skills that are needed is concerned, perhaps we should change our teaching methodology, even in the first years of university. We should change from the basic methods that we use and continue to use, and switch to focusing on how to use the results of the method. For example, Professor Capasso pointed out that there is too much emphasis on how to compute with the integrals and so all the work has to be done by hand. Of course, we still teach how to do this, but we also rely on other tools that complete calculations for us. So there is less focus on all that manual technique, but more on how to use it. Another change will be using the data that we get out of all of these systems, which means understanding and being critical of the data that you see – critical thinking and solving complex problems, not by doing the whole job, because you will get tools that are going to deliver you information and data, but you need to understand what they mean.

*Dimitri Loringett*: Jacqueline?

*Jacqueline Mock*: Actually my suggestion is much along your lines. It will be important especially for high school teachers to provide their students with guidelines on how to use such a vast amount of tools: access to the Internet, huge amounts of data, how to be critical and how to formulate decent questions so that students won't get lost in this immense space of information – and also misinformation! – that's out there.

*Dimitri Loringett*: That concludes our discussion. I thank those of you from the Schweizer Jugend forscht and the Science Olympiad CH and Professor Capasso for being with us here today.

## AFTERWORD BY CLAUDIA APPENZELLER-WINTERBERGER

Secretary General, Swiss Academies of Arts and Sciences

In the digital age, we need to reconsider the best ways for effective university teaching. Shall we rely on massive open online courses (MOOCs), on YouTube, or on robots? What will the role of professors be? Balzan Prizewinner Federico Capasso has presented some highly interesting details of the learning techniques he developed together with his colleague Eric Mazur at Harvard University. He claims that it is not simply delivering information, but rather developing questions and testing the validity of different approaches by the students themselves that can provide them with the foundations of scientific thinking. That is why we asked Federico Capasso, on the occasion of the Balzan Lecture 2018, to share not only his knowledge of the quantum cascade laser, but also his reflections and experience on his formative approach to learning. Professor Capasso agreed with pleasure, but on the condition that – in line with his new teaching methods – the lecture would not be *ex cathedra*, but rather discussion and testing his ideas with young students and researchers. We were happy that two organizations that promote young talents in Switzerland, Schweizer Jugend forscht and Science Olympiad Switzerland, provided us with the names of successful former participants, and that they agreed to join us.

In Capasso's and Mazur's project, "formative learning" means that students begin by annotating their textbooks with questions and engaging in discussion in an online platform. The successive phase entails "learning catalytics": short online questions and individual answers that are discussed until the students converge on the correct answer. Capasso refers to this as the "Socratic method in action". Explanations are then given and short experiments are performed in class. This is only one sequence in a whole set of activities aimed at fostering the art of questioning and discussing, as well as the ability to construct machines and devices – all part of an innovative curriculum leading to the master's degree. The focus always lies on the exploration of overarching problems and not on the rote learning of knowledge in a single discipline.

While some aspects of teaching can be successfully offered online, the social interactions remain important. Capasso stresses that horizontal interaction between professors and students as well as among the students themselves is more effective than the traditional top-down way of teaching. Students need their community, and this was also confirmed by the young talents who participated in the workshop. Some of them already had experience with question-oriented teaching in their own tutorials or at high school, and they all agreed on questions and discussions as the motivating factor. YouTube features and MOOCs are clearly viewed as valuable preparatory or supplementary tools. During the breakout session, the discussion went deeper: does it make sense in the digital age to have science students learn all the formulas and techniques by heart? Do they need this as preliminary groundwork, or could the traditional way of learning be replaced by an approach oriented more towards problem-solving or by interactive formats that foster scientific thinking and invite further exploration? How do we deal with large groups of students? One conclusion is clear: digitalization is not something which can be planned in a tech department: it also deals with social interaction. Tomorrow's professors and students will have to find the right channel to deliver information. Universities and academies should provide interaction and motivate young researchers to tackle societal challenges, such as climate change and energy – the "real difficult and exciting problems", as Capasso calls them. "Everybody should learn programming languages to remain active in a digital world", said one of the participants. "Do not leave the women behind in the digital age", concluded another, referring to the low number of women engaged in the STEM subjects in Switzerland.

With Federico Capasso, one more Balzan Prizewinner not only shows us his findings, but also indicates tracks that can be explored on a larger level in universities, schools and society at large. We would like to thank him and the Balzan Foundation for this exciting talk, as well as the young scientists who so very readily engaged in this interesting discussion!

## Federico Capasso

## BIOGRAPHICAL AND BIBLIOGRAPHICAL DATA

Federico Capasso, born in Rome on 24 June 1949, is an Italian-born and naturalized United States citizen (1992). He has been Robert Wallace Professor of Applied Physics and Vinton Hayes Senior Research Fellow in Electrical Engineering, Harvard School of Engineering and Applied Science, Cambridge, Massachusetts since 2003, and was formerly Adjunct Researcher at the Institute for Quantum Studies at the Texas A&M University.

After earning his doctor of physics degree, with honours, from the University of Rome, Italy, in 1973, and after research in fibre optics at the Fondazione Bordoni in Rome, he joined Bell Laboratories as a Visiting Scientist in 1976. In 1977, he became a member of the Technical Staff, becoming a Distinguished Member in 1984, and a Bell Laboratories Fellow in 1997. In addition to his research activity, he has held several management positions at Bell Labs, including Department Head of Quantum Phenomena and Device Research (1987-1997) and of Semiconductor Physics Research (1987-2000), as well as Vice President of Physical Research (2000-2002).

His honours include membership in the National Academy of Sciences, the National Academy of Engineering, the American Academy of Arts and Sciences, the Academia Europaea and honorary membership in the Franklin Institute. He is a Foreign Member of the Accademia Nazionale dei Lincei, Fellow of the American Physical Society, the Institute of Physics (UK), the Optical Society of America, the American Association for the Advancement of Science, IEEE and SPIE, and also holds honorary doctorates from Lund University, Diderot University (Paris VII), the University of Bologna and the University of Tor Vergata, Rome. He is a recipient of the IEEE Edison Medal, the American Physical Society Arthur Schawlow Prize in Laser Science, the International King Faisal Prize for Science, the SPIE Gold

Medal, the American Academy of Arts and Sciences Rumford Prize, the American Association for the Advancement of Science Newcomb Cleveland Prize, the IEEE Sarnoff Award, the Materials Research Society Medal, the Franklin Institute Wetherill Medal, the European Physical Society Quantum Electronics Prize, the Rank Prize in Optoelectronics, the Optical Society Wood Prize, the Berthold Leibinger Future Prize, the Julius Springer Prize in Applied Physics, the Institute of Physics Duddell Medal, the Jan Czochralski Award for Lifetime Achievements in Materials Science, and the Gold Medal of the President of Italy for meritorious achievement in science.

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Balzan Research Project

# TWO BALZAN RESEARCH PROJECTS

*Adviser for the Balzan General Prize Committee: Carlo Wyss*

With the second half of Federico Capasso's 2016 Balzan Prize for Applied Photonics, two research projects have been undertaken by his young researchers:

1. Optoelectronics and nano-photonics in two-dimensional nanomaterial heterostructures;
2. Quantum Effects in Complex Systems ('Q-EX').

## Project 1: Optoelectronics and nano-photonics in two-dimensional nanomaterial heterostructures

Institution: Harvard School of Engineering and Applied Science, Harvard University, Cambridge MA
Supervisor: Prof. Federico Capasso
Proposed beneficiary: Dr. Miriam Serena Vitiello (CNR NANO – Nanoscience Institute, National Enterprise for Nanoscience and Nanotechnology-NEST, Scuola Normale Superiore, Pisa)

The project is based largely on Dr. Miriam Serena Vitiello's ideas, and aims to explore novel electronic, optoelectronic, and plasmonic phenomena in the 2D vdW heterostructures, seeking device applications based on these nanoscale quantum structures.

Research will target radically new concepts and approaches to develop a novel optoelectronic technology based on 2D nanomaterials. All activities are driven by interdisciplinary methods and groundbreaking views, intersecting opto- and nano- electronics, photonics, material science and quantum engineering.

## Introduction

Artificial semiconductor heterostructures played a pivotal role in modern electronic and photonic technologies, providing a highly effective means for the manipulation and control of carriers, from the visible to the terahertz (THz) frequency range. Despite their exceptional versatility, they commonly require stringent epitaxial growth procedures due to the need of clean and abrupt interfaces, lattice matching or limited and controlled lattice mismatch, which proved to be major obstacles for the development of optoelectronic and photonic devices in the infrared.

The discovery of graphene has triggered an unprecedented interest in inorganic two-dimensional (2D) materials. Van der Waals (vdW) layered materials such as graphene, hexagonal boron nitride, transition metal dichalcogenides, and the more recently rediscovered black phosphorus (BP) display an exceptional technological potential for engineering nano-electronic and nano-photonic devices and components "by design", offering a unique platform for devising heterostructures with a variety of properties. Each layer can indeed be forced to simultaneously act as the bulk material and the interface, reducing the amount of charge displacement within it. However, the charge transfers between different layers can be very large, meaning that large electric fields can be induced, therefore offering interesting possibilities for band-structure engineering.

Furthermore, these material systems also provide an intriguing platform for fundamental investigations, through the exploitation of their confined electronic systems.

Finally, being fully compatible with a wide range of substrates including flexible and transparent ones, if placed on chip with flat integrated optical circuits, they can allow maximal interaction with light, therefore optimally utilizing their novel and versatile properties for a wealth of applications in transformational optics, optical communications, spintronics and high-resolution tomography.

A plethora of opportunities and novel functionalities can therefore appear when one starts to combine several 2D crystals in one vertical stack, allowing synergetic effects to become very important. The proposal aims to explore novel electronic, optoelectronic, and plasmonic phenomena in the 2D vdW heterostructures, seeking device applications based on these nanoscale quantum structures.

## Summary of specific objectives

1) Local investigation of the electronic and plasmonic properties of heterojunctions based on different 2D nanomaterials, developing novel scanning probe techniques in the far infrared, and specifically:

a) amplitude and phase sensitive near field microscopy with sub-10-nm spatial resolution;
b) near-field probes with integrated nanodetectors enabling large-area, high-resolution microscopy;

2) development of electrically controlled optical phase modulators with hBNgraphene / hBN;

3) development of novel nanoelectronic and photonic devices based on 2D nanomaterials and combined heterostructures.

## Outlook and impact

The targeted goal of the proposal is to provide groundbreaking technological steps toward the development of a new technology based on 2D nanomaterials aiming to trigger the development of applications across the terahertz and the mid-infrared.

Ultimate electronics applications of the project's proposed research would include, for example, flexible electronic systems that utilize the superior mechanical pliability of vdW materials. The development of novel high-performance nanoscale optoelectronic components prospects great impacts on future emerging signal processing and computer technologies. These new capabilities can be heterogeneously integrated into silicon CMOS based electronics. Optical / optoelectronic applications include photodetectors and integrated photonic systems. The proposed work plan will also provide fundamental understanding of the materials properties and phenomena underpinning these applications. In addition, novel quantum electronic, optoelectronic and nanophotonic devices have long been a focus in the device community because of the improved power / bandwidth performance possible with optical links for communication.

Almost every new 2D material possesses unusual physical properties. The 2D physics in such materials is just starting to emerge.

Still, the most interesting phenomena can be realized in van der Waals heterostructures, which now can be mechanically assembled or grown by a variety of techniques, prospecting the emergence of a new low cost technology that would finally allow full tackling of also the terahertz portion of the electromagnetic spectrum.

## Summary of achieved results

1. *Near-field probes with room-temperature nanodetectors for sub-wavelength resolution imaging*

Near-field imaging with terahertz (THz) waves is emerging as a powerful technique for fundamental research in photonics and across physical and life sciences. However, in the THz spectral range (frequency: 0.3-10 THz, wavelength: 30-1000 μ m) imaging is severely restricted by diffraction.

Spatial resolution beyond the diffraction limit can be achieved by collecting THz waves from an object through a small aperture placed in the near-field. However, light transmission through a sub-wavelength size aperture is fundamentally limited by the wave nature of light. To overcome the above limits, the team conceived a novel architecture that exploits the inherently strong evanescent THz field arising within the aperture, to mitigate the problem of vanishing transmission.

To this aim, they introduced a novel near-field probe architecture, where the evanescent THz field is converted into a detectable electrical signal at the nanoscale. The latter goal is achieved by integrating a THz nanodetector based on a thin flake of crystalline black phosphorus (BP) into the evanescent field region of a sub-wavelength aperture to enable efficient detection of the transmitted wave.

Their results pave the way to the development of new coherent THz microscopes for large-area sub-wavelength resolution phase- and amplitude-sensitive imaging. In combination with QCLs operating in the 1.5-5.0 THz range, this imaging technique can aid the development of novel optical components (mirrors, filters, metamaterials, metalenses and sub-wavelength resonators) and open new research avenues in the studies of fundamental light-matter interaction phenomena in many interdisciplinary fields crossing optics, photonics, chemistry and biology.

## Associated publications

1. O. Mitrofanov, L. Viti, E. Dardanis, M. C. Giordano, D. Ercolani, A. Politano, L. Sorba, M.S. Vitiello, "Near-field terahertz probes with room-temperature nanodetectors for sub-wavelength resolution imaging", *Nature-Scientific Reports* 7, 44240 (2017).

2. M.C. Giordano, L. Viti, O. Mitrofanov, M.S. Vitiello, Coherent near-field imaging at THz frequencies with enhanced sensitivity enabled, submitted to *Optica*.

3. M.C. Giordano, L. Viti, O. Mitrofanov, G. Scamarcio, S. Mastel, R. Hillenbrand, D. Ercolani, L. Sorba, M.S. Vitiello, "Sub-wavelength near field imaging techniques at terahertz frequencies", *Quantum Sensing and Nano Electronics and Photonics* XV, 10540, 10540N (2018).

### *2. Phase-resolved detector-less terahertz near-field microscopy*

Scattering-type scanning near-field optical microscopy (s-SNOM) offers exceptional potential for the nanoscale imaging of material properties, such as free carrier distribution, chemical composition, localization and propagation of plasmon, phonons and plasmon-polaritons and for capturing ultrafast dynamics in nanoscale-systems. Amplitude and phase resolved s-SNOM thereby enables access to the spatial variation of complex-valued dielectric responses and both the amplitude and phase of near-field distributions.

THz frequency electromagnetic waves can resonantly interact with fundamental excitations of molecules and solids and thus offer an ideal tool for the optical characterization of emerging low-dimensional materials and biological systems.

In s-SNOM, an incident THz beam is focused on a sharp atomic force microscope (AFM) metallic tip strongly confining the THz radiation in the near-field region of its nanometric apex. Nanoscale resolved (10 - 100 nm) optical images can be retrieved by analysing the scattered THz radiation as a function of tip position, placing the tip in close proximity to the sample surface. Both amplitude and phase contrast information can be obtained by employing interferometric techniques. These methods, however, increase the complexity of the experimental arrangement by introducing additional optical components such as modulators, translators, beam splitters and, particularly, detectors, which, in the THz spectral range, usually rely on cryogenically cooled bolometric systems to retrieve the typically low intensity signals.

Progress in the field is therefore restricted by the lack of compact, room-temperature and fast detection systems and appropriate passive optical components for THz frequency operation.

During the first year of the Balzan project, the problem was tackled by conceiving a simple, potentially compact, detector-less s-SNOM system that operates in the self-detection (SD) mode. It features a THz QCL that senses the backscattered optical field through a voltage modulation induced inherently through the self-mixing technique.

To provide a proof-of-principle of the amplitude and phase contrast imaging capability of the SD-s-SNOM, a polar crystal (CsBr), which exhibits a strong phonon-polariton (Reststrahlen) resonance in the 2.2 – 3.3 THz range, was selected. This demonstrates amplitude-and-phase-resolved background-free SD-s-SNOM imaging with a spatial resolution comparable to the scattering tip size, providing a key step forward to make THz nanoscopy a widely used tool.

Finally, the capability of the team's SD-s-SNOM to image doped van der Waals layered materials was demonstrated. To this purpose, they selected hBN/grahene/hBN heterostructures and black phosphorus (BP), a technique which made it possible to unveil acoustic photons at THz frequencies in graphene, by capturing gate dependent s-SNOM signals in double-gated FETs and to determine carrier concentrations in Se-doped BP via optical contrast effects in the far-infrared.

## Associated publications

M.C. Giordano, S. Mastel, C. Liewald, L.L. Columbo, M. Brambilla, L. Viti, A. Politano, K. Zhang, L. Li, A.G. Davies, E.H. Linfield, R. Hillenbrand, F. Keilmann, G. Scamarcio, M.S. Vitiello, Phase-resolved detector-less terahertz near-field microscopy, submitted to *Science Advances*.

## Project 2: Quantum effects in complex systems ('Q-EX')

Institution: Princeton University, Princeton, NJ; Polytechnic University of Milan
Supervisor: Federico Capasso
Proposed beneficiary: Dr. Margherita Maiuri (Chemistry, Princeton University, and Physics, Polytechnic University of Milan)

This project is inspired by the hypothesis that, if nuclear motion influences quantum dynamics of natural and bio-inspired molecular systems, it should be possible to extend a similar argument to the study of exciton dissociation in 2D materials and their hetero-structures. The key hypothesis of vibronically assisted charge separation in 2D heterostructures still lacks experimental evidence. Direct observation of the complex quantum dynamics at the 2D TMD interface will be one of the challenges of Q-EX project, with the outcome of generating important photo-physical insights and suggesting design principles for operation of ultrathin devices under non-equilibrium conditions.

### Introduction

Recent advances of ultrafast laser spectroscopy have promoted deep studies of quantum effects in complex systems where excitons – correlated electron-hole pairs – play a central role in light-triggered dynamics. In the excitonic picture, the spatial extent of an electronic excited state is increased thanks to a coherent sharing of the excitation among subunits of the system. This quantum-mechanically coherent superposition of states evolves in time and, if strong, can be observed by spectral features that are perturbed, shifted, or split. These properties are determined by electronic coupling among the repeat units forming the material, and strongly depend on the type of complex system involved.

Since these discoveries, the idea of quantum coherence in charge and energy transport has been extended and established from biology to a number of other photovoltaic materials and nanoscale systems. Particularly important are atomically thin two-dimensional materials, such as graphene and transition-metal dichalcogenides (TMD) MX2 (M = Mo or W, X = S, Se), which have come into the spotlight due to their outstanding physical properties. The extremely high carrier mobility of graphene and the tunable direct band gaps of TMDs highlight the crucial role that quantum confinement can have in producing several technologically relevant electronic properties.

## Summary of specific objectives

Q-EX aims to explore the roles that nuclear motions play in the ultrafast exciton dissociation in two different complex systems, going beyond the framework of classical electron transfer Marcus theories. The project has two main objectives:

(a) the study of excitonic many-body effects in 2D materials and their heterostructures;
(b) the study of vibronic coupling in bio-inspired molecular arrays.

## Summary of results

1. *Excitonic interactions in 2D materials and their heterostructures (Politecnico di Milano)*

The extremely high carrier mobility of graphene and the tunable direct band gaps of TMDs highlight the crucial role that quantum confinement can have in producing several technologically relevant electronic properties. Due to the low dielectric constants and the strong quantum confinement effects, Coulomb force is poorly screened in single-layer TMD materials, so that the excitons created by photoexcitation have huge binding energy, up to 1 eV. In the single-layer (1L) limit, they exhibit an indirect-to-direct band gap transition, which is accompanied by efficient light emission in the NIR-visible range. In addition, the coupling of spin and valley degrees of freedom gives rise to valley-selective optical properties. TMDs offer also the exciting possibility of creating heterostructures, obtained by stacking one material on top of the other. Such systems, which are analogous to classical semiconductor heterostructures, display rich optoelectronic properties due to the bandgap mismatch of the different components.

During the first year of the project, the team developed a multidimensional ultrafast optical technique, namely two-dimensional electronic spectroscopy (2DES) to understand the non-equilibrium optical properties of TMDs and their heterostructures. They are able to report one of the first 2DES measurements obtained on a 1L MoS2 sample, provided by collaborations with the Cambridge Graphene Centre (Prof. Andrea C. Ferrari). 2DES is the elective tool for the experimental studies of this project, since it measures energy / electron transfers and electronic couplings in multi-absorbing systems. Thanks to its main advantage of providing simultaneously high temporal and spectral resolution, it is possible to disentangle spectrally congested features, such as the different electronic transitions in complex systems and many body effects.

In 2DES, three consecutive incoming pulses with two separate controllable delays impinge on a sample. This interaction creates a nonlinear polarization that emits a field from the sample, after a delay t. The emitted field can be fully resolved in amplitude and phase when it interferes with a fourth pulse (local oscillator) or with the third pulse by itself. By Fourier-transforming the signal with respect to the first tau and t at a fixed T delay, one can retrieve a 2D map as a function of excitation and detection frequency for a specific delay T. By correlating excitation and detection axes, it is possible to track the energy flow dynamics and detect electronic couplings between excited states.

Their preliminary results show three 2DES maps at specific T delays. These preliminary data, combined with deeper analysis and supported by calculation, might help to better understand the intricate ultrafast transient response in prototypical 1L TMD, such as bandgap renormalization and Coulomb exchange interactions. This is a crucial step before moving on to the study of the heterostructures.

## Associated outcome

M. Maiuri, S. Dal Conte, M. Russo, J. Wang, G. Soavi, D. Dumcenco, A. Kis, A.C. Ferrari, G. Cerullo, Excitonic effects in single layer MoS2 probed by two-dimensional electronic spectroscopy. Manuscript in preparation. Submitted to MRS Fall Meeting (2018).

*2. Vibronic coupling in bio-inspired molecular arrays (Princeton University)*

Organic small molecules, such as tetrapyrroles, play crucial roles in numerous processes in nature, serving as cofactors in proteins where they have several functions. For example, chlorophylls (which contain magnesium ions) are responsible for photosynthetic electron and energy transfer, whereas hemes (which are iron porphyrins) contribute to the transport of diatomic gases. Synthetic porphyrins are exploited for artificial light harvesting, ultrafast electron transfer in donor-acceptor complexes, and in organic solar cells. Characterizing the photoinduced ultrafast processes involved in these molecules is necessary for understanding such processes.

During the first phase of Q-EX project, Dr. Luca Moretti has been appointed as Visiting Associate Researcher at Princeton University to study the electronic interaction in artificial tetrapyrroles arrays. First results report on a comprehensive pump-probe investigation on recently synthetized arrays of zinc porphyrins (containing from two to six molecules) which have shown strong excitonic interactions. The samples will be provided by Professors Gust, Ana Moore, Tom Moore (Arizona State University).

## Associated outcome

L. Moretti, B. Kudisch, Y. Terazono, A. Moore, T.A. Moore, D. Gust, G. Cerullo, G.D. Scholes, M. Maiuri, Excitonic Effects in non-rigid Zinc-Porphyrin Arrays Studied by Sub-25 fs Near-UV Pulses, manuscript in preparation. Contribution to ESP conference (2018).

# PROFILES

## The International Balzan Foundation

The *International Balzan Foundation "Prize"* aims to promote, throughout the world, culture, science, and the most meritorious initiatives in the cause of humanity, peace and fraternity among peoples, regardless of nationality, race or creed. This aim is attained through the annual awarding of prizes in two general academic categories: literature, the moral sciences and the arts; medicine and the physical, mathematical and natural sciences. Specific subjects for the awarding of Prizes are chosen on an annual basis.

Nominations for these prizes are received at the Foundation's request from the world's leading academic institutions. Candidates are selected by the *General Prize Committee*, composed of eminent European scholars and scientists. Prizewinners must allocate half of the Prize to research work, preferably involving young researchers. At intervals of not less than three years, the Balzan Foundation also awards a prize of varying amounts for Humanity, Peace and Fraternity among Peoples. The *International Balzan Foundation "Prize"* attains its financial means from the *International Balzan Foundation "Fund"* which administers Eugenio Balzan's estate.

## The Swiss Academies of Arts and Sciences

The Association of the *Swiss Academies of Arts and Sciences* includes the Swiss Academy of Sciences (SCNAT), the Swiss Academy of Humanities and Social Sciences (SAHS), the Swiss Academy of Medical Sciences (SAMS), and the Swiss Academy of Engineering Sciences (SATW) as well as the two Centres for Excellence TA-SWISS and Science et Cité. Their collaboration is focused on methods of anticipating future trends, ethics and the dialogue between science, the arts and society. It is the aim of the *Swiss Academies of Arts and Sciences* to develop an equal dialogue between academia and society and to advise Government on scientifically based, socially relevant questions. The academies stand for an open and pluralistic understanding of science and the arts. Over the long-term, they mutually commit to resolving interdisciplinary questions in the following areas:

– They offer knowledge and expertise in relation to socially relevant subjects in the fields of Education, Research and Technology.
– They adhere to the concept of ethically-based responsibility in gaining and applying scientific and humanistic knowledge.
– They build bridges between Academia, Government and Society.

## The Accademia Nazionale dei Lincei

The *Accademia Nazionale dei Lincei*, founded in 1603 by the Roman-Umbrian aristocrat Federico Cesi and three other young scholars, Anastasio De Filiis, Johannes Eck and Francesco Stelluti, is the oldest scientific academy in the world. It promotes academic excellence through its Fellows, whose earliest members included Galileo Galilei, among many other renowned names.

The Academy's mission is "to promote, coordinate, integrate and disseminate scientific knowledge in its highest expressions in the context of cultural unity and universality".

The activities of the Academy are carried out according to two guiding principles that complement one another: to enrich academic knowledge and disseminate the fruits of this. To this end, the Accademia Nazionale dei Lincei organises national and international conferences, meetings and seminars, and encourages academic cooperation and exchange between scientists and scholars at the national and international level. The Academy promotes research activities and missions, confers awards and grants, publishes the reports of its own sessions and the notes and records presented therein, as well as the proceedings of its conferences, meetings and seminars.

The Academy further provides – either upon request or on its own initiative – advice to public institutions and drafts relevant reports when appropriate. Since 1992, the Academy has served as an official adviser to the President of the Italian Republic in relation to scholarly and scientific matters.

AGREEMENTS ON COLLABORATION BETWEEN
THE INTERNATIONAL BALZAN FOUNDATION "PRIZE",
THE ACCADEMIA NAZIONALE DEI LINCEI AND
THE SWISS ACADEMIES OF ARTS AND SCIENCES

(Hereafter referred to as the 'Balzan', the 'Lincei' and the 'Swiss Academies', respectively)

The main points of the agreements between the Balzan, the Swiss Academies and the Lincei are the following:

1) The promotion of the Balzan Prize and the presentation of the Prizewinners through the academies' channels of communication, in Italy and Switzerland as well as abroad. By virtue of the relations of the Swiss Academies and the Lincei with academies of other countries and with international academic organizations, they will contribute to more widespread circulation of news related to the Balzan;

2) On the occasion of the Awards ceremony of the Balzan Prize, held on alternating years in Berne and Rome, each academy will contribute to the academic organization of an interdisciplinary Forum, in the course of which the Prizewinners of that year will present their academic work and discuss it with other academics proposed by the academies. Furthermore, in the years when the ceremony is held in Rome, one of the Prizewinners will give the Annual Balzan Lecture in Switzerland, and when the ceremony is held in Berne, the Annual Balzan Lecture will be organized at the headquarters of the Lincei in Rome;

3) The academies will contribute to a series of publications in English (ideally with summaries in Italian, German and French), created by the Balzan, with the collaboration of the Balzan Prizewinners.

To promote and supervise all these initiatives, two Commissions have been set up, one between the Balzan and the Swiss Academies (at present composed of Maurice Campagna and Dr. Markus Zürcher) and another between the Balzan and the Lincei (at present composed of Sergio Carrà and Paolo Matthiae). Both commissions are chaired by Professor Alberto Quadrio Curzio as a representative of the Balzan, which is also represented by Professor Enrico Decleva. The Balzan Secretary General, Dr. Suzanne Werder, has been appointed Secretary of both Commissions.