

## Photons continue to surprise: a conversation with Harry Atwater

**Jennifer Dionne**

Stanford University, Palo Alto, California, United States

**Jennifer Dionne:** Thanks everyone for joining. My name is Jen Dionne. I am a professor of material science and engineering, and also, by courtesy, of radiology, at Stanford University. I also have an appointment at SLAC through my role as deputy director of Q-NEXT, a DOE National Quantum Information Science Center. I'm thrilled to be interviewing Professor Harry Atwater today. Harry is currently the Otis Booth Leadership Chair of the Division of Engineering and Applied Science at Caltech. He's also the Howard Hughes Professor of Applied Physics and Material Science, and the director of the Liquid Sunlight Alliance. Harry was my PhD research advisor. I can't thank him enough for everything he taught me from science to management to proposal writing, and I'm thrilled to be talking with him today about solar and thermal photonics for a theme issue for *Advanced Photonics*. Thanks so much for joining us, Harry.

**Harry Atwater:** Delighted to be here and always a pleasure, Jen, to touch base again and talk science.

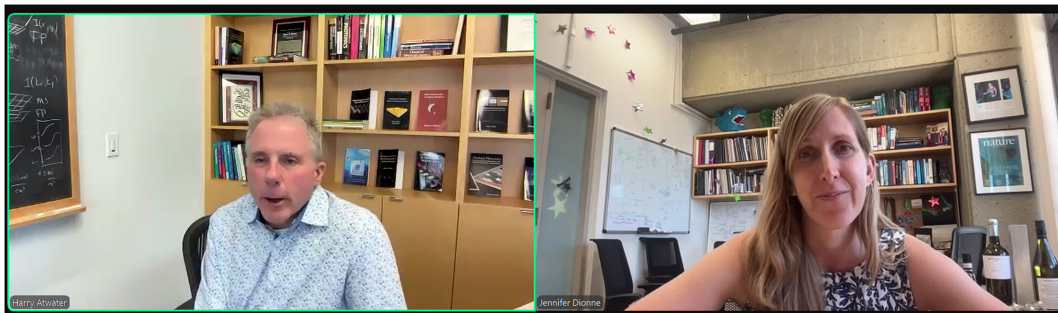
**Jennifer Dionne:** The first question I wanted to kickstart our conversation on is just asking you a little bit about your scientific journey. What got you interested in science? What led you to material science, physics, photonics, and how did you get to be a professor at Caltech? What was your journey that led you up to that point of your career?

**Harry Atwater:** Well, I started out by being an apple that didn't fall far from the tree. My father was also a professor of physics. So I guess from an early age I assumed that was something that was at least achievable, and he certainly made it seem like a really fascinating and exciting journey in life. And so I follow in my father's footsteps. But I would say also another formative aspect, since the subject that we're talking about with solar and thermal photonics actually impinges on the whole larger subject of energy, I would say that the probably seminal

event that got me launched on this path is when I was in high school we went through what is now known in retrospect as the first energy crisis. Back in the mid-1970s, and there was a period of a month when I grew up in Pennsylvania, where it gets cold in the winter, where my school was unable to be heated because the heating source was oil and there was not enough oil—and the school had to be closed down for a few weeks in the wintertime. We had gasoline rationing depending on whether your license plate was odd or even. That experience had made a big impact on me—a big impression—and I vowed that someday if I got to the world where I was doing science for myself, I would try to do something that would have some impact on this energy situation.

**Jennifer Dionne:** Wow! Very cool. I don't think I realized that your dad was a professor of physics. I also hadn't appreciated quite how bad the energy crisis was in the 1970s, with gas rationing and people having to conserve energy based on their license plate numbers! So, given that high school experience, did you major in material science then in college when you went to MIT, or what was your pathway?

**Harry Atwater:** I was an electrical engineer, and I guess at MIT at that time—maybe it's still true—that meant pretty much license to do whatever you like. And so I learned about materials and I learned about physics. I concentrated in physics and did EE, and then went on to graduate school in electrical engineering as well at MIT. My first research project as a graduate student was focused on making thin-film solar cells back in 1983. This is back before the world had its first megawatt of solar PV installed. And of course, now we're a thousand times greater than that, past 1 terawatt. So that has been really to me an eye-opening and ultimately affirming and exhilarating story to see solar grow over my professional lifetime. I had the good fortune of being able, when I launched my independent career at Caltech, to begin



*Advanced Photonics* associate editor Dr. Jennifer Dionne (right) interviewed Dr. Harry Atwater, Otis Booth Leadership Chair of the Division of Engineering and Applied Science at Caltech, Howard Hughes Professor of Applied Physics and Material Science, and director of the Liquid Sunlight Alliance. Readers are invited to enjoy the interview also in video format, <https://doi.org/10.1117/1.AP.7.3.030501>.

working in solar and energy and photonics immediately. This was not a time when it was a hugely fashionable subject, and there wasn't much solar capacity. This was in the late 1980s and early '90s, when people weren't really thinking about it that extensively. And it really burst onto the scene in the 2000s when the world's capacity for making solar PV and the need for it really began to meet, and people started taking it very seriously. During that time, as a faculty member, I got involved in our common passion and obsession of plasmonics and nanophotonics, really looking at how light interacts with the subwavelength-scale world. That also opened a new window for how to manipulate light, something that we shared and still share, and that influenced my work in photovoltaics, and then also in thermal energy conversion. And so from there, we began working on very high efficiency solar cells, using the best available materials at the time, which were III-V compound semiconductors, and we ended up making record efficiency single-junction solar cells and modules operating at 1 sun, founding the company called Alta Devices. That was an interesting journey. We made very efficient cells, but in gallium arsenide the challenge was to reduce the cost, and the cost of silicon solar photovoltaics dropped so rapidly that we couldn't keep keep up, and Alta Devices never really became the world dominating company that we hoped it would, even though it did achieve scientific records that still stand today, actually, some of these solar cells.

**Jennifer Dionne:** Yes—I was going to say—my understanding is that you still hold the record for some.

**Harry Atwater:** That's right. So now we're somewhat proud of this, that even 13–14 years later the record still stands. And by that time, of course, both you and I had gotten into thinking about manipulating light in all of its dimensions and scales. And so one of the things that I think was really interesting, and something that continues and I'm very actively focused on right now, is the question of how you take seemingly incoherent radiation from a luminescent dipole, or from a thermal dipole, and endow it with some degree of coherence. We're both familiar with the seminal work of Jean-Jacques Griffet, showing that thermal dipoles coupling into phonon polaritons that travel on the surface of a silicon carbide crystal then form a well-defined surface wave that can be coupled out by grading into free space. And this was a really exciting thing at the time, back in 2005 when he did this, to show that this seemingly—you know, we think of blackbody radiation as being Lambertian in its angular distribution and broad, spectrally broadband—and so what we've learned, of course, in the interim is that with thermal radiation and infrared radiation, we can manipulate it in terms of its spectral and spatial components pretty significantly. And that's really, to me, quite interesting, the idea of seeing coherence emerge from what appear to be incoherent sources.

**Jennifer Dionne:** Cool! Tons to unpack there. I have probably questions to fill many dozens of hours, but I want to go back to some of the conversation on solar, to understand some of the advances there. I think it's really neat how you combined your PhD experience making solar cells with your expertise in photonics to think about how you can structure back-contacts or nanostructure the active material. I remember when I was a PhD student, you and your lab were doing pioneering work on these nanowire solar cells that had radial p-n junctions. You mentioned Alta Devices, where I think some of the record efficiencies were created by essentially either removing the material from the substrate or actually controlling the light between materials. Could you speak a little bit about the advances in photonics and how those have impacted solar PV?

**Harry Atwater:** Well, one of the things that we have as a sort of guidepost to go by in design of photovoltaic structures and devices is the

principles of detailed balance, the flux balance between radiative absorption and emission. And that's actually the thing that got me excited about thermal photonics as well. And so we know from that that the condition that leads to the maximum efficiency of a solar cell is, somewhat paradoxically, the condition that you have luminescent photons extracted from the cell. It seems more intuitive that you would want to simply trap as many photons in the cell and not let them be re-emitted at all. But this principle of detailed balance and radiative flux balance tells us that the luminescent emission is necessary in the radiative limit to reach the maximum efficiency. You can't reach the maximum of absorption unless you have this radiative emission. So that ended up being a design principle that we employed in the cells. That—and what you referred to at Alta Devices—we made cells by epitaxial liftoff, where we peel off, like peeling a sticky label off a sheet of sticky labels, so you could peel off a thin film cell, instead of having it be on an absorbing substrate. If you put it on a highly reflective substrate, the photons could, with very little loss, be reflected back, and then efficiently extracted to the desired extent to maximize the radiative efficiency of the cell. And so we ended up being able to show that this luminescence extraction is a principle that governs the efficiency of cells, which was exciting. It was really a privilege to be able to work with these high radiative efficiency materials, where you could actually see these fundamental limits. We also showed, for example, that you can improve the voltage of a solar cell by extracting and narrowing the angular distribution relative to the entire maximum entropy condition of emission in all directions. And so a number of exciting features, where you feel like you're talking to the fundamentals of photonics, and they're talking back to you, and you're seeing the manifestation in the efficiency of the solar cell, which is pretty exciting.

**Jennifer Dionne:** Very cool. How do you think that radiative flux balance and photonic design principles will factor into photovoltaic cells of the future? Or, put otherwise, where do you think there are core areas for innovation and improving upon the PV cells that have already infiltrated the market?

**Harry Atwater:** Well, I think one area where these principles can be tested very elegantly is in the hybrid halide or organic-inorganic halide perovskite materials where, similar to gallium arsenide, the radiative efficiency is very high. You know, technologists are currently trying to overcome the instability issues with these cells, but when you make them freshly in the lab, the rate of efficiency is extremely high and you can really test some of these fundamental limits for photonics using these materials. And in fact, I can imagine that, if the stability issues, the environmental stability and durability issues, can be addressed, these might be—full stop—the most efficient cells that technologists have ever been able to create. It's just that last step of being able to guarantee the environmental stability which has been still an outstanding challenge. You know, we ended up starting a company called Calix Solar Energy. It started out on working on the silicon microwire and nanowire cells that you described. And we realized that silicon was going to become so cheap, so quickly, that we pivoted and Calix now today is working on halide perovskite on silicon tandem cells, to try to boost the efficiency, and now going into small-scale production of these tandem halide perovskite silicon tandems—the idea being to combine the most widely manufactured cells with the ones that could provide the highest efficiency.

**Jennifer Dionne:** Very cool. Switching gears a little bit and talking still about photons: you mentioned this mystery of how it is that incoherent radiation can be endowed with coherence. Before we get into thermal photons and thermal PV, I wanted to see if there's any link between that concept and what you're doing

with the Liquid Sunlight Alliance and chemistry and analysis—and how photonics has fueled, in a way, nature's form of chemical manufacturing.

**Harry Atwater:** Well, the Liquid Sunlight Alliance is a hub program focused on the subject of artificial photosynthesis: how you emulate nature's fantastic example of directly creating chemical fuels and chemicals and fuels by redox reactions. And so, instead of extracting electrons into the external circuit like you would the solar cell to power some electrical load you're driving—redox reactions that, for example, reduce water to form hydrogen, molecular hydrogen, or oxidized water to form the protons that are the precursors to molecular hydrogen or reduction of CO<sub>2</sub>, which is really the major focus of the Liquid Sunlight Alliance now. And there, the goal of developing artificial photosynthetic devices is to emulate nature's examples of harvesting sunlight producing chemical products, but doing it much more efficiently than nature. The biological limits are in the few percent range and biological systems tend to optimize themselves for biological viability rather than efficiency. And so, you know, engineered systems that we work with that use the same semiconductor materials that we use in photovoltaics could be in principle much more efficient. In fact, we've developed prototypes showing water splitting at almost 20% efficiency and similar for reduction of CO<sub>2</sub> to simple reduced products like carbon monoxide. So we can now, at least in lab champion prototypes, we can perform those unit processes of doing simple reduction reactions with almost the same efficiency as we can convert electricity to sunlight.

**Jennifer Dionne:** That is really amazing. What are your thoughts on how you might scale some of these photoreactors? Or how do you create these reactions at scale, but using light efficiently in a chemical reactor?

**Harry Atwater:** Right? Well, okay. So one of the things to do is to learn the lessons from photovoltaics if we're going to work with engineered rather than natural materials. I should say there's a whole stream of this field of artificial photosynthesis in which people are working with molecular chromophores. Our particular approach is to work with solid state chromophores that are bulk, solid materials like photovoltaic materials. But you can also work with molecular chromophores as nature does. But so going forward, the Liquid Sunlight Alliance is aiming to harvest all the advances that have been made in gigawatt- to terawatt-scale photovoltaics and really exploit these highly optimized photovoltaic electrodes as the engines for artificial photosynthesis—the premise being that if we can do this, then they would immediately be scalable to a very large scale. And so the scientific questions are: How do you efficiently drive the reactions? How do you overcome some of the seemingly beguiling and fundamental problems related to the high over potentials for carbon dioxide reduction or for water oxidation? These are still outstanding challenges in photochemistry. And how do you solve these durability problems? When you work with redox reactions, you're inherently producing chemical products. And you want to produce products that you desire; you don't want to produce products from the actual device, corroding or eroding the device to produce the products. So that's one of the big challenges in the durability of these materials is to selectively drive reactions, use selective catalysis to drive the reactions that you wish and the ones that you're trying to avoid.

**Jennifer Dionne:** That's right. In my opinion, one of the most exciting things about using photons to drive chemical reactions is that now you're no longer in thermal equilibrium, and you can open up these excited state pathways that can get you selectivity that otherwise is impossible when you're just using heat.

**Harry Atwater:** Yeah. By the way, that brings you back to the work that we began with in plasmonics, where we studied for many years and where I think we're still fascinated by the light localization in small metal particles. I've been a contributor but there are many others who have contributed in this general field of plasmonic photochemistry, where you can recognize that if you could harvest the hot carriers that are produced in photochemical reactions using metal particles, you could actually access chemical states that are way out of equilibrium. It's a big challenge though, because you have to do this very fast. The relaxation times of hot carriers are on the hundreds of femtoseconds to picosecond scale. They're not long-lived carriers like we have in inner band absorption in a semiconductor, but if you could master this it could be a very interesting pathway. And mastery of that requires going down to the fundamental time and length scale. It's on the subnanometer size range so it's really, truly a nanoscience arena. But it's exciting. There are new advances all the time. Our common friend and colleague, Emiliano Cortez, is showing some beautiful examples of relatively efficient water splitting, using these kinds of devices, and I think if we can master the ability to harvest and then prevent the ultimate relaxation of hot carriers on this short length scale this could also be a very exciting avenue. It's tantalizing because it's easy to end up with a device that's inefficient, that produces mostly heat. But if you can figure out a way to harvest the hot carriers, it could be a very exciting direction.

**Jennifer Dionne:** That's neat, and maybe in a way similar to the work that you did on PV. I really admire how the work in the Liquid Sunlight Alliance and in your lab is combining the best of both metals and semiconductors, and getting synergistic effects between those contacts to be able to drive really efficient reactions.

**Harry Atwater:** Yeah, well, semiconductors are, as we know from the example of photovoltaics, already quite efficient. Some of the materials are now becoming quite mature. And so this is something you can definitely exploit. And actually, in the case of silicon and perovskites, they're also quite cheap, which is interesting.

**Jennifer Dionne:** Yep, absolutely. Now shifting gears to thermal photons, I wanted to talk a little bit about the work that you've done in collaboration with Professor Eli Yablonovitch on thermal photovoltaics, work to harness some of these lower energy photons that otherwise might be lost as heat, but can actually be converted into useful forms of energy. So maybe talk us through how thermal photovoltaics work, your research in that area, and what you think the future holds?

**Harry Atwater:** Well, thermophotovoltaics refers to using a photo cell, not a solar cell but a photovoltaic cell, to harvest photons from our infrared heat source, instead of it being that big heat source in the sky. Some other hot source—it could be a solar furnace, it could be a combustion process—anything that can harvest infrared photons. And I think that the major thing, that major contribution that Eli made, and I had the good fortune to work with him on, is to recognize that the same factors that make gallium arsenide solar cells as efficient as they are for solar photovoltaics also obtain in the case of thermophotovoltaics. And then the key thing in thermophotovoltaics is simply to design the structures that recycle photons as efficiently as possible so that they are fully and very efficiently absorbed in the semiconductor material. So this is a very interesting direction. We held the record for a short while, and now I think there's a group at MIT that holds the record for most efficient thermophotovoltaic device, which is now getting up in the same realm as photovoltaic devices in the 20s and 30s of percent, which is quite interesting.

**Jennifer Dionne:** Very cool—and then, in terms of when you think about the future of thermal photovoltaics, you mentioned you can

use any IR heat source—do you foresee TPV would be using, say, waste industrial heat, and converting that into energy? Or where do you think most of the core application areas would be?

**Harry Atwater:** Well, it's an interesting question. And I think our Caltech colleague and former collaborator, Brendan Kayes, has gone off into the world of industry, and he's working with Antora Energy. And their concept is that heat is something that can be stored like electrons in a battery and that once you've stored heat in some high heat capacity medium, maybe after the sun has gone down, you can now convert it back to electricity, using thermophotovoltaics. Their scheme is to use a heat source on a high heat capacity liquid metal or liquid salt which can be heated to relatively high temperature, and then extract photons efficiently from that source, and thereby make photovoltaics available on demand even after the sun goes down.

**Jennifer Dionne:** Cool. Yep, and that's kind of a perfect segue into one of the topics you mentioned right at the top of the hour: thinking about thermal photons. So have you thought a little bit about the intersection of how you might efficiently store heat and release it on demand, and how that relates to photonic principles of controlling thermal radiation.

**Harry Atwater:** Yeah, well, I think the thing that I have been excited about recently is the idea of going back and revisiting this phenomenon that Jean-Jacques Griffet pointed out that thermal photons or thermal dipoles in a solid can couple into propagating waves that then develop spatial coherence, and they can be diffracted or reflected or guided, just like a wave that came from an originally coherent source, and especially if you have some way to impose spectral coherence. So one way you could do that would be to make your absorbers now be resonators, optical resonators that have resonant frequencies in the infrared. And now then that means your spectral distribution is no longer that of just an ordinary black body with unity emissivity. But you end up with a more spectrally narrow band source. Once you start with a narrow band source, then you can start to pin down a specific wavelength and wave vector, for a propagating wave. And then it's just a matter of—now of course, these thermal dipoles will all be incoherent with one another—but as they are guided along in a structure they have, essentially, coherence with themselves, and we know from work in which we couple light into surface waves, that we can couple it back out again. And so I think that's a very interesting opportunity. We're currently exploring this as a way to create a new kind of luminescent solar concentrator, using what we call an external luminescent solar concentrator, where you illuminate with sunlight a chromophore, like quantum dots couple the quantum dot emission. And all the quantum dots are incoherent with one another, but couple them into a surface mode, where each the photons from each can couple out coherently into the far field, so thereby coupling out at an angle which is then intercepted by a photovoltaic cell which would give rise to concentration—a new kind of concentrator that goes beyond the waveguide concentrators that have been built in the past.

**Jennifer Dionne:** Yeah, that's neat. For those listening in, when you're talking about thermal photons, what is the wavelength that you are most interested in looking at? And how do we think about not only wavelengths of light, but the spatial scales of these wave guides or resonators that are controlling thermal radiation?

**Harry Atwater:** Yeah. Well, so the infrared extends all the way from the limits of our own vision, at 700 or 800 nanometers or so, all the way to 10 or 20 microns. But at the peak, if you think about the black body spectrum at the surface of the earth at 300 kelvin that peaks between 8 and 14 microns—so when I think of thermal infrared, I think of that range between about 8 and 14 microns. If you think about the

applications for thermal photonics, that is obviously low-grade heat energy temperatures at or slightly above 300 kelvin. And that's the realm, as the globe warms and people living in temperate and equatorial regions seek out air conditioning, we're going to be looking at to enable radiative cooling as much as possible for turning our cities from being urban heat islands into cool zones. And that's going to be an engineering challenge to efficiently extract heat and to use similar principles for recovering and recycling lower grade waste heat that is otherwise difficult, and relatively inefficient, to process.

**Jennifer Dionne:** That's neat! Just for those listening in who maybe are new to the field—you talked about radiative cooling—could you help define it and add a little bit more color and perspective? Because I think that's such a unique concept.

**Harry Atwater:** Yes. Well, our good friend Shanhui Fan, your colleague at Stanford, pointed out a few years ago that—just like we were talking about in the design and design principles for photovoltaics—we have detailed balance between radiating objects, solar cells, and the sun, but we can equally well think about something like a solar cell or a solar radiator, and not the sun, but instead, the cold background of space. And so, just as the sun radiates photons to a solar cell, we can convert the energy so we can radiate energy at the earth's surface towards the cold background of space, and essentially enable a sort of energy conversion, and that energy conversion could be the local cooling of something relative to the local ambient background. Or you could even use that emitted photon stream to generate an electric current.

**Jennifer Dionne:** Yeah, that's very cool. And I think Shanhui used this to power an LED.

**Harry Atwater:** Indeed. Yes, but more broadly, I think the real opportunity is in just thermal radiative cooling, without any other active or moving parts. Figuring out how to do that efficiently with very simple materials, is something that seems very attractive and potentially scalable, as we have cities that are becoming warmer all the time, and growing all over the world as the planet warms.

**Jennifer Dionne:** That's a perfect segue into a question I wanted to ask you, which is when you're thinking about these materials to control thermal radiation or enable radiative cooling, what are the sorts of materials needed? And is there a way to start incorporating some of those materials into future city construction or industrial design?

**Harry Atwater:** Well, of course, there have been some simple ideas. When Steve Chu was Secretary of Energy, he famously advised the Queen of England to paint the roof of Buckingham Palace with white paint, and she politely declined. I guess that was related to the aesthetic and historic conditions of the palace, but that would have been the right answer from the point of view of radiative heat transfer, because that, of course, is reflecting solar photons. And that white paint is also quite black in the infrared, and therefore it emits thermal photons very efficiently, and can enable cooling below the background. So that, I think, is an interesting direction, to think about materials that we could develop as roofing materials or paving materials, things that coat the surfaces of vehicles, or all kinds of dwellings, that would allow us to manipulate thermal radiation and the energy saved. It's quite interesting to think that the energy you could emit by just passive thermal radiative cooling could be comparable to the energy from a medium efficiency photovoltaic panel. So, suppose you did the thought experiment: a solar panel is collecting sunlight, electricity is driving an air conditioner, and you compare that to a radiative cooling panel that's the same size. You can get about the same cooling power from both, which is quite interesting, because the radiative cooling panel is much simpler.

**Jennifer Dionne:** Yeah, very cool. You know, when I consider some of the biggest challenges the world will face in sustainability, I think a lot of them boil down to advances in materials. I'm curious, when you envision the future of sustainability—whether it's in areas that you've pioneered in photovoltaics, thermal photovoltaics, artificial photosynthesis, or even carbon capture—where do you find the most compelling needs for materials advances and development of new materials—whether it's two-dimensional materials or heterostructures—where are the biggest needs in materials? But then, also, where do you think are the biggest “blue-sky spaces” for exploration, where those entering the field can dive in and not feel like it's a crowded space?

**Harry Atwater:** Okay, yeah, all right. This is now speaking to the assistant professors and the graduate students. So well, first of all, the field of materials is just like a movable feast. There are always going to be new materials that are exciting to study. I have new materials that I'm playing with right now that I am fascinated by—I don't know what they're good for, but they're certainly a lot of fun to play with—so that will always be the case. I would say that one of the lessons from having worked in solar energy and thermal energy and carbon capture is that scalability has to be a pretty important consideration, so that's an important thing to think about. It's usually relatively easy to start at the early stage of an investigation and figure out what something would be scalable to the terawatt scale or not, whether you could cover a large fraction of the world's rooftops with the material and or not, and then that can guide your thinking about where to go next. But yeah, the world of materials is fascinating. I'm fascinated now by materials that break reciprocity of photon transport, so-called Lorentz reciprocity materials that can play tricks with our ordinary notions about how photons propagate. I'm not sure exactly where those will land in terms of applications, but they're certainly interesting to think about.

**Jennifer Dionne:** Yeah, actually just diving in there, since I think it ties in so nicely with some of the other topics you mentioned: if you have a nonreciprocal material, my understanding is that you can break the equality of absorptivity and emissivity, so with some of the photonic materials that you talked about earlier, in principle, you could create even more efficient devices.

**Harry Atwater:** Right? Yeah, this is something that our good friend Shanhui Fan had predicted almost 15 years ago, and this prediction was out there. It was sort of a challenge. And recently we did some experiments that were able to for the first time demonstrate this so-called violation of Kirchhoff's law, which shows the breaking of reciprocity between absorption and emission. And so we've been able to do it first narrow band and then somewhat broader band over a swath of the long wavelength infrared, and we can't quite yet make the emittance be 0 and 1 at will, but the breaking of reciprocity between absorption and emission is now something that has been seen now by a number of groups. So it's kind of exciting.

**Jennifer Dionne:** That's neat! Cool! So you mentioned scalability of materials as something that needs to be built into the mindset, or thinking through of a solution, right away. Reciprocity is an interesting new area where people could explore. What would you say is a difficult challenge of developing nonreciprocal materials? Is it the incorporation of magnetic fields or time varying fields? What might be some of the challenges to overcome, to break reciprocity?

**Harry Atwater:** Well, you put your fingers on it. We know of several ways. This is what Lorentz taught us, that we could either break reciprocity and time symmetry by applying a magnetic field—we know this from simple devices, like Faraday rotators and other common in optics—also by making the field be time varying, so that by the time

the signal comes back to us it has a different waveform and intensity and amplitude, and so forth, than it did at the beginning, or also by parametric generation using materials that do frequency conversion. So those are the ways that we know of at the moment. And there are inherent technical challenges in working with each of those kinds of materials. All of them have to be effectively active. That means we have to do work on the material somehow, in order to get the benefit of reciprocity. One exception, I guess I would say, is materials that have their own internal magnetic field. You're essentially doing work against the internal magnetic field. But yeah, I think all these are interesting areas and areas for future work on breaking reciprocity.

**Jennifer Dionne:** Very cool. And then one final question: you've done incredible work, on the fundamental science, but then also on the translational work, and I don't think I can even count how many companies you've started—including Aonyx and Alta, which you mentioned, and Captura, which is doing—

**Harry Atwater:** —carbon capture. Yes. Carbon dioxide, carbon capture.

**Jennifer Dionne:** From oceans! What sort of advice would you give to researchers who are thinking about the interface of lab to translation? How do you go about that process of bringing advances in the lab out into the world and into the hands of customers or end users?

**Harry Atwater:** Well, first of all, just like with scientific research, it doesn't happen all by itself. It requires a passionate messenger and evangelist who is willing to do it. That's probably the most important thing. Second, is establishing that somebody in the world cares, and that person cares enough to invest in you financially to push it forward, past the R&D stage. And if you have those two things, then that carries you a long way. At some point, having a polished and professional CEO, who can point you in the right direction and make things really happen in the business world, is helpful. So I would say, those three things are important, but it always starts with the same sort of passion that we bring to scientific research—the similar passion directed in the direction of translation.

**Jennifer Dionne:** In talking about passion, if you had to succinctly kind of summarize what you are most excited about for the next 50 years of your career, what might those scientific topics be?

**Harry Atwater:** Well, I think photons continue to surprise. They're very reliable in that, in being endlessly amusing. So that is, I would say, great career insurance for both of us. And so I think this question of the shades of gray between coherence and incoherence is a potentially deep and vast subject. We tend to think and bin our thinking in photonics into mostly working with light that's coherent. And, in fact, most light sources are actually partially coherent. And so I think, thinking about that. And then also, you can now go in the direction of temporal correlations, things that are not only spatially coherent, but temporally coherent and spatial temporal coherence. So I think that's a really interesting direction for the future, and you know, plenty of fundamentals to tackle.

**Jennifer Dionne:** Cool. Thank you so much. Is there anything I should have asked you that I didn't?

**Harry Atwater:** Well, first of all—and this is reflecting on my partner here—I am so inspired by the people I have had the privilege to work with, including yourself and now a long line of people. And that's the thing that enables everything that I do—as you've experienced yourself, almost all of the great things happen in small teams, and rarely is the work that we do a solo sport. I'm grateful to your partnership

beginning a long time ago and continuing. And I would say that's my observation, to all those who are also participating and listening.

**Jennifer Dionne:** Awesome. What a great way to end. Totally agree. And I think the beauty of science is that we are all able to collaborate with each other and work on the challenging problems—and hopefully

bring those to solutions that the world can benefit from. Thank you so much for your time, Harry.

**Harry Atwater:** Thank you for taking the time as well.

**Jennifer Dionne:** Appreciate all your insights.