Views

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Disruptive: making lenses in a foundry

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So far, people have thought of optics as mainly consisting of bulky lenses. A team from Harvard University has started to change that. Federico Capasso, the leader of this team, aspires to nothing less than a new kind of optics [1]. His flat lenses, known as metalenses, perform wavefront shaping with nanometer-tall and -wide structures. In a breakthrough reported this year [2], he and his team demonstrated a metalens that focuses all the colors of visible light in the same focal spot of size limited by the diffraction of light. No existing single lens can do that: to make such achromatic lens, a stack of multiple lenses is required, with precisely controlled curvature and optical alignment, which leads to greatly increased weight, thickness, and cost.

Federico Capasso is Robert L. Wallace Professor of Applied Physics and Vinton Hayes Senior Research Fellow in Electrical Engineering at the John A. Paulson School of Engineering and Applied Sciences, Harvard University in Cambridge, MA, USA. Image courtesy of Eliza Grinnell, Harvard University.

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While applications such as super-thin cellphone lenses are appealing, it is the manufacturing process that excites Federico Capasso: metalenses can be made by conventional lithography used in the fabrication of electronic chips, as his group recently showed [3]. No more molding and polishing: optics and electronics can be made in the same fab. AOT Editor-in-Chief Michael Pfeffer talked to Federico Capasso on his invention and its applications. Andreas Thoss edited and shortened the 40 min conversation.

Pfeffer: Meta-lenses and meta-optics have a potential for disruptive change in modern optics. Can you tell me how that all began?

Capasso: Yes, I think it started with the paper that I published with my group in Science in 2011 [4]. What we found is generalized laws of reflection and refraction for surfaces patterned with subwavelength spaced optical elements, known as metasurfaces. That was quite amazing. That paper has now more than 2000 citations. The key point is that one can design the angles of refraction and reflection for the incident light, and so one can make new lenses with major advantages compared to commercial ones.

Pfeffer: If we think about meta-optics, how would you characterize that?

Capasso: I don't know if you had the chance to see it, but if you look on YouTube, for 'Meta Lenses' [5], you will find a beautiful video, which *Science Magazine* created on occasion of the publication of our paper reporting the first high-performance metalenses in the visible [6]. It made the cover of Science and was voted by its readership as one of the 10 breakthroughs of the year.

Pfeffer: Yes, that one is wonderful.

Capasso: Basically, my vision is that metalenses and other metaoptical components will be made with the same lithographic processes used in the fabrication of integrated circuits such as the silicon sensor chip in a camera. It will have far reaching technology and business implications. The most fascinating of these for me is that there will be a Moore's law, not only for electronics, but for optics.

Even though optics and photonics, penetrate in all our gadgets, they still by enlarge use technology based on lenses as developed long ago in Jena, Germany.

Otto Schott, Carl Zeiss, and Ernst Abbe… They really created modern optical technology, but it's based on lens molding. Of course, lens molding was known for a long time already. In the early days, it was called 'lens grinding', polishing. That was Galileo. He learned from the Dutch. Then, in the 19th century, those famous three Germans, made it into an actual fabrication technology: molding.

Surprisingly, even though it's been greatly perfected, it's still fundamentally the same. It is a complex and costly process.

Now I take as my favorite example, a camera module. It is composed of about six lenses. You have two technologies co-existing: on the one hand, you have the planar technology of sensors and integrated circuits, and then, you have the lens technology, with mostly curved surfaces and molding processes to make them. They are hard to match. The optical alignment is more difficult and costly than if the lens were flat.

And this leads to another thing because they are curved; lenses are inherently thick. You know the hero achromatic refractive lens is the famous superachromat by Zeiss. It's a beautiful, fantastic piece of engineering. It corrects for all the aberration including chromatic, but it's thick and weighs quite a bit.

Now, our metalenses are thinner, and aberration correction is inherently simpler. For the first flat lens, which was before the one that had a big splash in 2016, we started with a very simple, flat profile, and we could easily correct for spherical aberrations. To achieve that, a refractive lens must be shaped in a very specific way (aspherical lens) and with extreme precision using a very expensive machine.

I think this points to a future where the entire camera module (chip and lenses) will be made in the same foundries. That's our vision [1, 3]. The same foundries that will make the chips, the sensors, will also fabricate the lenses, the metalenses. Why? Because the technology, the process, that we have developed, atomic layer deposition of titanium dioxide [7], is compatible ultimately with integrated circuit fabrication, which is done with so called deep-UV steppers, which perform the required lithography using ultraviolet light (UV).

That is sort of the big picture I have in mind.

Pfeffer: How did you come up with the idea of making a flat lens?

Capasso: I was working on quantum cascade lasers, and I was collaborating with one of the world's most famous atmospheric chemists, Professor Jim Anderson, here in [Harvard's] chemistry. In fact, he co-wrote the famous Montreal Protocol for the Ozone Hole.

He had been flying quantum cascade lasers in his drones to measure atmospheric chemicals in difficult-to-access regions. One day, he came to me and said, 'This optics in front of my cascade laser occupies too much space. Can you make a QCL that is collimated and doesn't need any lens?' It was a fantastic question.

With one of my students, we set out to it and published our first paper [8]. You could say it's a first step towards metaoptics, where we made essentially a contact lens for a QCL. By patterning with grooves and so forth one of the laser facets, we managed to dramatically reduce the divergence of the laser beam and collimate it by interference.

That was a start. We followed with a paper [9] where we collimated a terahertz laser, which was much more difficult. Then, all of a sudden, things clicked together. You know how it is in research. We realized, why are we putting this stuff on the facet of laser? Why don't we ask the more general question? We made what people started to call 'metasurface' [4]. In addition to redefining the laws of refraction and reflections, we showed that metasurfaces could be shaped to create optical beams of any shape starting from optical vortices and far more complex and weird wavefronts.

The way to do that is conceptually simple. We first design the required phase profile of the metasurfaces. Then, we digitized it by putting close enough to each other the optical elements (the 'ones' and 'zeros' to closely mimic the desired profile, which is, of course, analog. The bottom line is that you can create arbitrarily structured light as we recently reported [10], a wonderful example of how one can create complex intensity patterns, in this case counterintuitive combinations of optical vortices that change depending on the polarization of light incident on the metasurface.

Pfeffer: So what is it after all? Diffractive optics like Fresnel optics?

Capasso: Yes, ours is diffractive optics, but it is a different kind. If you look at Fresnel lenses, they have typically all these zig zags and so forth, which cause all sorts of unwanted optical artifacts: shadowing, halos, and rainbows. And the irony is this: Even though they are called diffractive lenses, it's very hard for them to give a diffraction-limited focus (size λ over two, divided by numerical aperture) and practically impossible to make an achromatic lens and to correct aberrations with the precision of refractive optics. In metalenses and metaoptics, in general, the optical elements are basically vertical pillars or nanofins of the same height, with rigorously vertical walls and of varying cross sections. This greatly simplifies design and fabrication.

Pfeffer: Now, what about applications?

Capasso: Let me share this story with you. When I received a call from the head of the Google Glass project, after we reported the first flat lens in 2012 [11, 12], he said, 'Come and give a talk on this stuff.' I asked him, 'You realize that this is so far from applications, it's inefficient.' He said, 'It's very interesting. Come and talk.' There, I met the chief optical scientist at Google, Bernard Kress.

Pfeffer: Yes, I know him.

Capasso: Who since moved to Microsoft. He made an illuminating comment: 'the key advantage of metasurfaces is that you can design and implement an arbitrarily phase profile, for example, any lens you wish, with a single level of lithography, i.e. a single mask. Ones and zeros. Instead of having all these complicated profiles of Fresnel optics.' That opened my eyes.

We got a number of really exciting developments ever since. We can now, using a single metasurface, replace multiple optical components and also simultaneously implement multiple functions. These can be then be accessed by changing the incident polarization, wavelength, or direction of incident light. I tell you can find a stunning example of this in a paper we published just a few weeks ago [13]. My group made a metasurface that depending on which of three or four design wavelengths (blues, green, red, and yellow) is used, it acts like a lens or a vortex beam generator.

Now, take polarimetry, which deals with measuring and generating polarized light. This is one of the areas of potentially greatest impact for flat optics. Take a polarimeter, which measures the polarization of light; it requires multiple phase plates including a rotating one. Here is how the story developed. We published a Science paper a few years ago [14] where we showed that we could stir the direction of propagation of surface plasmon waves on metallic metasurfaces by changing the incident polarization. Then, we realized they didn't need to be surface plasmons. It was enough to have an array of metallic structures, arranged in a certain way so that as you changed the incident polarization, the light would actually be scattered here, or here or there, depending on the design of the array. By measuring the intensity of light scattered in these directions, we determined the Stokes parameters of the incident light and, therefore, its polarization with the same accuracy of a bulky, much more complex expensive commercial polarimeter [15].

Another thing we did is a compact spectrometer. You know very well that a high-resolution spectrometer is long because it's based on dispersion by a grating. So if you want to have sub-nanometer resolution, you have to have at least 1 m. Then, there is the collimator and the focusing mirror. We made one, which was essentially 1 cm long [16]. Here's the cool thing. What made it possible is a metalens that is highly dispersive. As you change the wave length, the focal point changes across the sensor. We can then separate the wavelengths as well as a 1-m-long spectrometer. Now, to be fair, we haven't yet demonstrated a large spectral bandwidth. But you know, it's in the making.

Pfeffer: This sounds amazing. I am looking forward to follow up those exciting developments with Advanced Optical Technologies. Thank you very much for this interview.

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