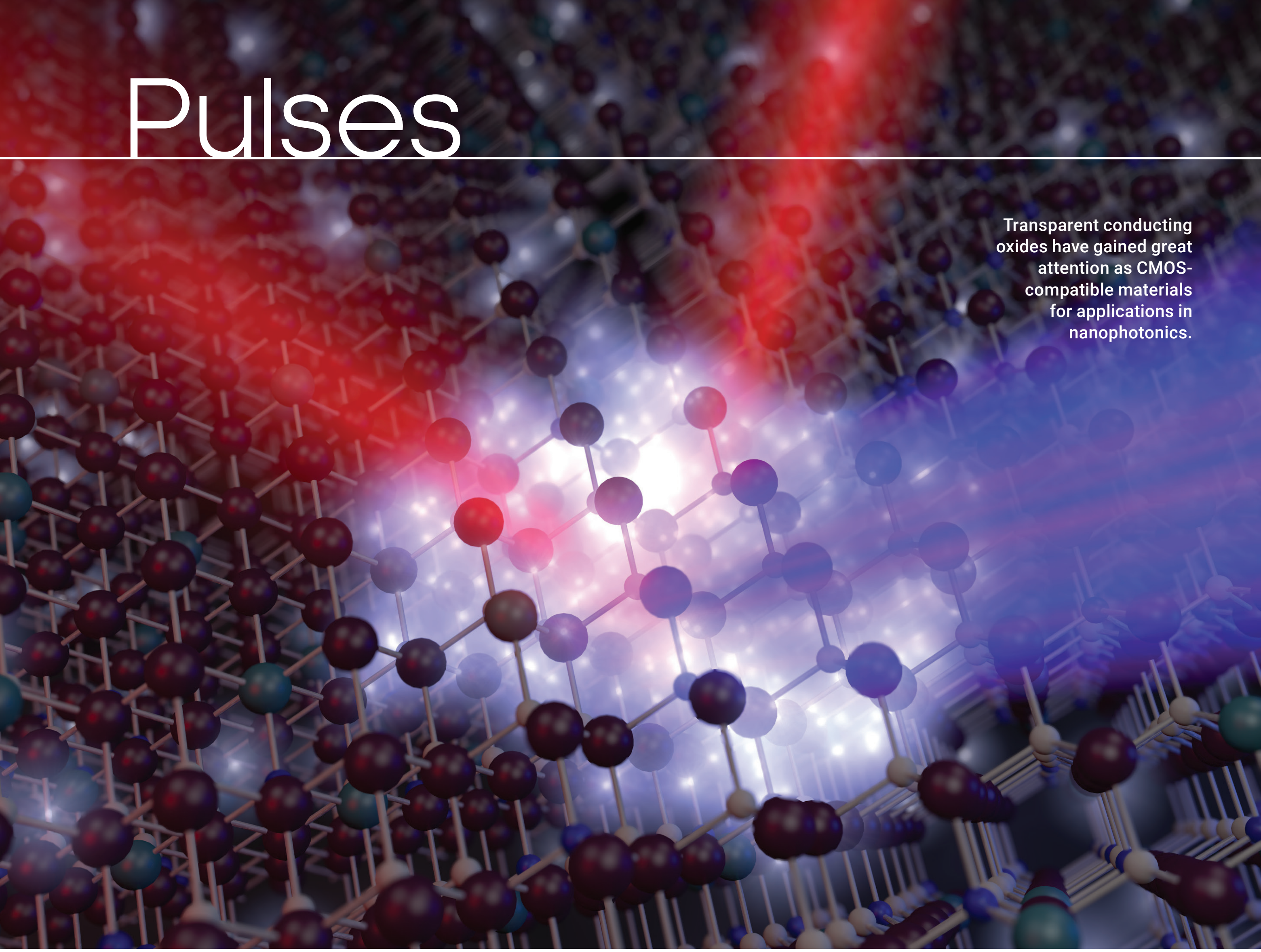


Optica **2**, 616 (2015)

CONVERSATIONS

Tailorable Materials for Dynamic Photonics

Alexandra Boltasseva spoke with OPN about how advances in materials science could enable new optical technologies.

Alexandra Boltasseva, Purdue University, USA, specializes in nano- and quantum photonics, plasmonics, optical materials and metamaterials. She spoke with OPN about her team's recent research in tailorable and tunable materials, and the prospects for productive collaborations between materials science, optics and engineering.

Q. Can you tell us about some of the work your team has been doing?

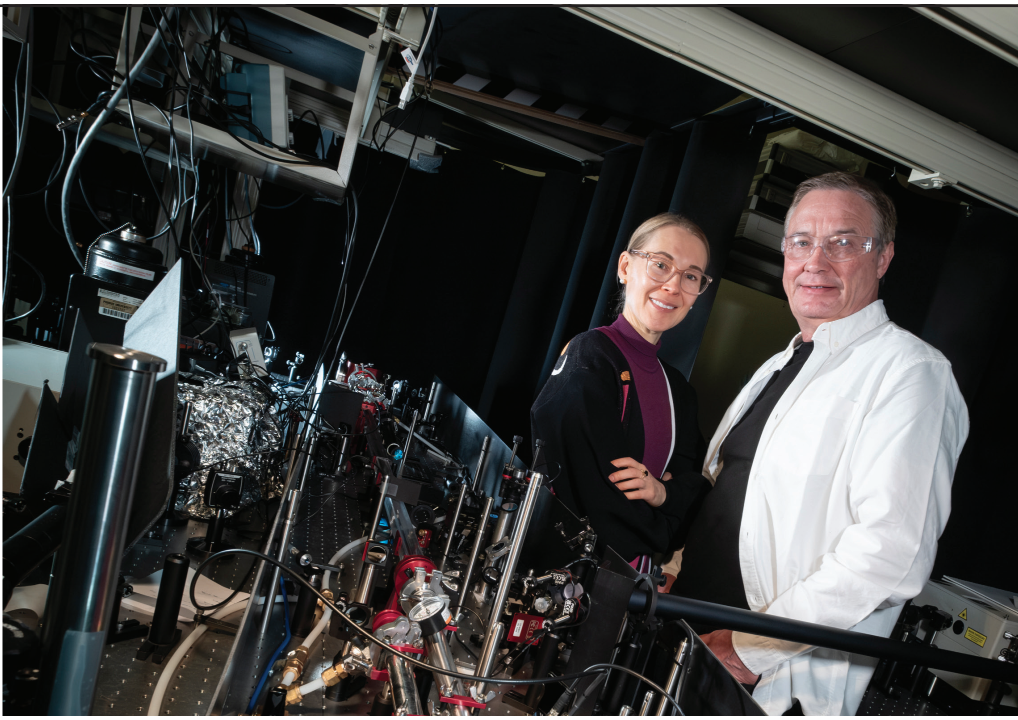
For quite some time, my team has been working at the intersection between materials science, engineering and photonics. Everything starts with a material, and I always emphasize the importance of connecting these disciplines to enable both new fundamental effects in optics and the exploration of unknown territories—and most importantly, to allow the new concepts to be translated to technology.

We focus on fundamental research because disruptive new technologies and applications come from advancements in fundamental science. We want to change things dramatically, not provide incremental improvements. Thus, we start with the exploration of a new phenomenon or concept, and then investigate which materials, architectures and device designs can drive the new idea to practical applications. For that, working as a team is the key. I don't believe in a single-man empire, I think that collaborations and teamwork are crucial. My group is an integral part of a larger photonics team—my "academic family," co-led by my colleagues Prof. V. Shalaev and Prof. A. Kildishev—at the highly interdisciplinary Purdue Nanotechnology Center, which hosts faculties from different disciplines, so our work is very collaborative.

Q. What kind of materials are you working with?

Recently, among others, two classes of materials have emerged as promising candidates for novel applications in optics. The first is a class of semi-metals, specifically, transition metal nitrides, which behave similar to conventional metals in the optical range and have some very beneficial properties. They are robust under different operational conditions, are scalable and can be tailored. For example, transition metal nitrides have attracted a lot of attention in nanophotonics, specifically, metal-based optics called "plasmonics," because they resemble metals in their optical response but can be adjusted to exhibit either dielectric or metallic properties. They have this interesting regime where the real part of the dielectric permittivity is close to zero (epsilon-near-zero, ENZ), and this region is tunable.

A new research direction that emerged from these materials we called "transdimensional photonics" because it resides between truly 2D systems and conventional thin films. Such materials that are just a few atomic layers thick exhibit many interesting effects that could lead to new applications in flat optics with metasurfaces, tunable planar photonics and nonlinear and quantum optics.



Researchers Alexandra Boltasseva (left) and Vladimir Shalaev in the lab at Purdue University, USA.
Purdue University

> "We want to change things dramatically, not provide incremental improvements."
> —*Alexandra Boltasseva*

The second material platform is a class of transparent conducting oxides (TCOs) such as indium tin oxide and doped zinc oxide, which have long been known in optics and optoelectronics as transparent electrodes and display panels. They are conducting, but they are also transparent in the optical frequency range, i.e. have very low absorption. We have been working with these interesting materials for quite some time, and they hold great promise for applications in all-optical switching and low-loss reconfigurable photonics. TCOs also exhibit a low-loss, highly tunable ENZ region that currently drives a number of exciting applications in nonlinear optics and dynamic photonics. A recent collaboration with the Technion team led by Prof. M. Segev is on exploration of ultrafast optical switching in TCOs with the potential to realize photonic time crystals.

Q. How are the materials tailorable, and why is this beneficial?

When you have a new idea or a device concept in mind, you must find a suitable material to start with. In photonics, we used to "stick" to conventional materials that are readily available. For example, for plasmonic applications, we would usually choose gold or silver. But for many applications, these materials are not tailorable or tunable and/or not robust enough. What we have

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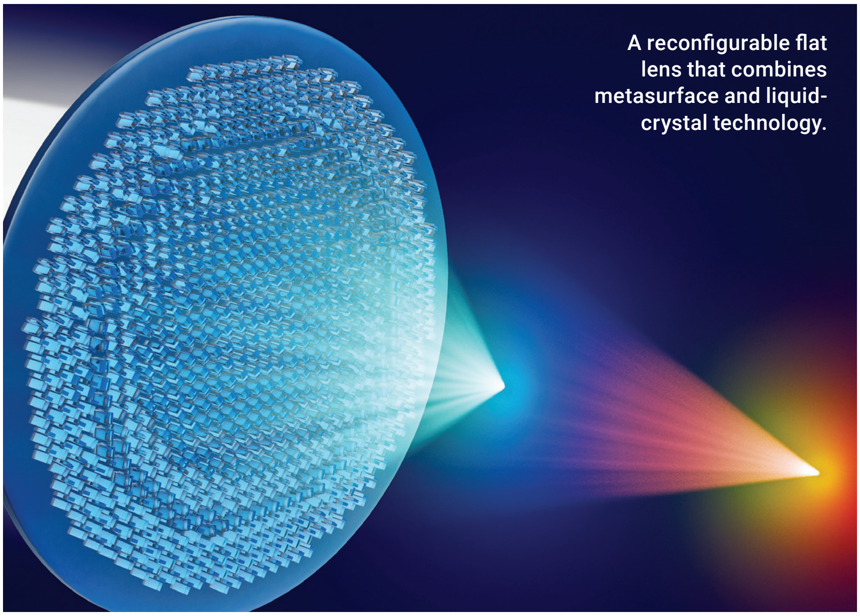

A reconfigurable flat lens that combines metasurface and liquid-crystal technology.

been missing in photonics is to have materials that are highly adjustable, similar to in the semiconductor area where one can control and tailor the properties of a materials in a wide range—for example, by doping, growth conditions, strain or stress.

Now in optical science, we are getting access to these "knobs" that we can tune, so that we can choose whether our material is more metallic or more dielectric at specific wavelengths. And this is important, because one can design and engineer the material to exhibit a precise property at the desired wavelength. For example, for TCOs I can choose the doping concentration and the deposition condition such that the ENZ point is at the exact wavelength needed. And having the ENZ point at the operational wavelength means that the device will have a very strong modulation at moderate excitations, critical for achieving, for example, all-optical switching. By changing the stoichiometric composition of the material, the deposition conditions and/or substrate, one can choose the region where your material is dielectric or metallic, and you can play around with losses and the dynamic response.

> "Our primary interest is in all-optical modulation because you can do it on an ultrashort time scale."
>
> *—Alexandra Boltasseva*

That was also the reason why we started to work with transdimensional films that change the optical response very efficiently under various external stimuli such as electrical bias, strain or optical excitation. Thus, we gain access to changing metallic properties in a similar way that we have been doing it in semiconductors, by changing the film composition, doping, substrate and deposition conditions.

In addition to such "static tailorability," there is also dynamic tuning, which is changing the properties of the material after it's already made, like a reconfigurable device. Our primary interest is in all-optical modulation because you can do it on an ultrashort time scale.

Q. What's next for your research?

One of the most important things in being successful in research is to see what is next. You should be looking into what's coming in the next five, 10 years, while at the same time doing both fundamental and applied research that is relevant for the current technologies. Right now, we are witnessing two technology revolutions: in AI and quantum. Bridging these disciplines, as well as leveraging the discoveries in both quantum and AI in optics is extremely important, and that's a path to disruptive advancements.

We started to work on quantum photonics before the "quantum wave" because we saw it coming and realized that fundamental quantum science should soon merge with engineering. We aimed at leveraging all the new ideas and concepts in photonics, especially nanoscale, on-chip photonic circuitry to see how we can drive the field of nano- and quantum photonics further. We now work on gaining ultimate control of quantum emission on a chip, developing single-photon sources, single-photon detectors and more.

And the same goes for AI. We started to apply machine-learning approaches for our work and photonic design quite some time ago, not only for inverse design, but also for advancing optical measurements in the quantum regime.

Combining these approaches, classical, quantum and machine learning, to designing very powerful and efficient photonic devices is very important, and that's where a lot of interesting advances will happen in the coming years. OPN