Mohammad Hafezi (left) talks with meeting attendees.

OSA

CONVERSATIONS

Demystifying Topological Order with **Photons**

Q&A with **Mohammad Hafezi** and **Jacob Taylor**

Optics & Photonics News had the opportunity to sit down and talk with Mohammad Hafezi and Jacob Taylor—two of the hosts from OSA's recent incubator meeting on topological order. Taylor is a group leader at the Joint Quantum Institute, which is a research partnership between University of Maryland and the National Institute of Standards and Technology, College Park, Md., U.S.A. Hafezi is an assistant professor at the University of Maryland and a fellow at the Joint Quantum Institute.

Q. What led you to organize an OSA incubator on this topic? What has made the time particularly ripe for this discussion?

JT: We've been working for a while, with other groups, on developing topological systems using light. In the last few years, it's become clear that there are a number of different people working on the topic, but we aren't really talking to each other. Mohammad and I were trying to figure out a way to create a community for us. How do we get everyone in the same room?

MH: In organizing the meeting, we also worked with two other hosts—Steve Girvin at Yale, who has done pioneering work in quantum Hall physics and topological order and, more recently, in circuit-QED systems; and Karyn Le Hur at the École Polytechnique in France, who has been doing fundamental and influential research in the context of quantum simulation using photons.

Q. Well, let's talk about "topological order" itself—that's a term that may not be familiar to all of our readers.

MH: Topology is just a way to classify a physical system—the same way we classify systems by how massive they are, what their color is, what their size is. The classic example is the donut and the coffee cup: geometrically they're different, but you can deform each of their shapes without cutting to make them identical to each other, and therefore, they are topologically identical. However, we can never deform a ball into a donut without punching a hole in it.

JT: And topological order has to do with the properties of the system that reflect only the topology. In the case of the donut and coffee cup analogy, you ask "Is this something I can hook my finger through or not?" Systems with topological order have some "thing" you can observe that depends only on its topology—how the pieces of the system are put together. Topological order tells you whether or not the topology matters.

Q. And one place that topology matters is in topological insulators, which have been a very big deal lately in condensed-matter physics.

MH: Right. In a topological insulator, the material is an insulator in bulk, but conductive on its edges. Now we're going back to the topology—because if the system didn't have an edge, then the conductance couldn't happen. The bulk states are localized and don't contribute to conductance, but the edges do. You can deform the edge of the system, but as long as you still have an edge, you have the same conductance.

In optics, of course, you can't have an "insulator," because it's not a conducting system. But you can have an analog in a system that, for example, transmits light on the edges but has a photonic band gap in bulk.

Q. So in a sense, this is about taking some of these interesting states from material systems—things like topological insulators—and simulating them in the photonic realm.

JT: Well, it's motivated and inspired by what's happened in the condensed-matter realm, but the optical realm has different possibilities. People have been taking mostly theoretical knowledge about these systems and using it to solve certain problems. Some of these problems are quantum problems—for example, how do I build a quantum simulator? And some of the problems are much more photonics problems: How do I build passive or active photonic devices on a chip that perform better than current designs? In both cases, understanding the condensed-matter side provides a framework for what we can imagine on the photonic side.

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>
> *—Mohammad Hafezi*

Q. The early part of the meeting seemed to focus on these systems in the context, particularly, of silicon photonics. How will topological order play a role in those systems?

MH: In that case, we're looking at something like classical information processing with photons—how can we transmit and maybe compute information on a chip. People are more interested in this with silicon-based technology, because it's more developed and easily integrated with CMOS technology.

But there are many building blocks that are missing—for example, a non-reciprocal system that acts like a diode. Another element that people have been trying to create is an optical transistor that operates at a few-photon level. There's ongoing effort in many groups.

Q. A large part of the meeting, though, moved away from silicon as a platform, and discussed metamaterials and photonic crystals from the perspective of topological order.

MH: Yes—this was really fascinating, exploring how we can mold the way light is travelling with metamaterials and photonic crystal systems. Our hope is that maybe this new idea of topology will provide some new ideas about how to deform the propagation of light.

Q. How might that work?

JT: The interface between crystals might appear completely uniform. But if it's a topological interface, there's a slight change: One half has one type of topological order and the other has a different order. There's a boundary between the two, and you can imagine using that boundary as a waveguide. There are some really rich possibilities in this realm of topological order.

Q. What were some other big themes in topological order with photons that you tried to capture in organizing this meeting?

JT: One of the questions was: How do you characterize topological order? The tools and theoretical systems for these photonic systems and for these bosonic systems are not clear. A lot of the meeting was dedicated to developing these questions, not necessarily answering them.

Another chunk of the meeting was dedicated to asking, "How are we going to get at interactions between individual photons?" I would say our tentative conclusion is that people who are interested in the problem will probably have their own incubator, because more and more people are getting interested in it.

Q. And why is that important?

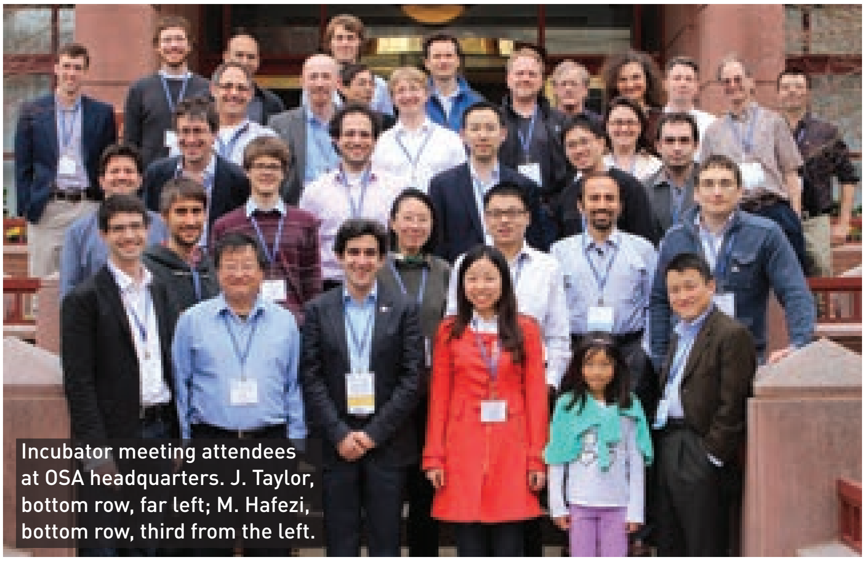
MH: Once we have control on individual photons, we can exploit their quantum nature and can encode information into the quantum state of photons. It can be polarization of a single photon or presence or absence of a single photon. So, first of all, topological robustness may have applications in quantum information processing to make devices that have this built-in protection.

But, part of quantum information science is actually quantum simulation—simulating systems that are hard to simulate with a classic computer. It turns out that this is a very hard problem that a lot of people are attacking from different angles—atoms on optical lattices, ion traps, photons in superconducting systems, and also with optical photons. Some questions in quantum simulation are related also to topology, so that's how they are all interconnected.

Q. So in some sense the work enables you to create quantum systems that, in turn, let you understand better topological order.

JT: We hope so! One of the first things you might do when you can get photons interacting on a single-photon level is start addressing challenges you can't address with a classical computer. I'm hopeful that this is something we'll get to see in the not too distant future.

The other thing is there are fundamental questions about what happens in complicated quantum systems. A lot of these questions are easier to answer for topological quantum systems because they are simple and robust to device imperfections and things that might go wrong within the system. They are a natural first target for quantum simulators.


Incubator meeting attendees at OSA headquarters. J. Taylor, bottom row, far left; M. Hafezi, bottom row, third from the left.

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"A different kind of challenge is developing a language that better connects the engineers and physicists."

—*Jacob Taylor*

Q. In the wake of this incubator, what things strike you as some of the biggest challenges ahead in this field?

MH: One of the biggest experimental challenges is having strong nonlinearity at the optical level. In the past year, it has been shown that it is possible. But can we do it in a scalable fashion? Like an integrated chip rather, than a single optical transistor?

One of the biggest theoretical challenges is that we don't know what to measure in some cases. We expect that some of these many body systems have an interesting topological order. But it's not clear what the "observable" should be. A peculiarity of photonics systems is that they are open—photons come in and photons go out. So, we have to build formalisms and preparation and measurement adapted for these open systems.

JT: Yes—nonequilibrium problems are hard! But in some ways a different kind of challenge is developing a language that better connects the engineers and physicists. Some of the challenges to physicists seem trivial to engineers, and vice versa. Having a better dialog at the interface of these two fields will continue to be very important for the success of this new field.

Q. And that's really one point of these incubator meetings—to spark new discussion and collaboration.

MH: Yes. We were glad to have physicists, engineers, theorists and experimentalists in attendance. We brought people from different fields who wear different hats together. It was a great meeting in that respect, and I hope it has both reinforced existing collaborations and created some new ones. OPN

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