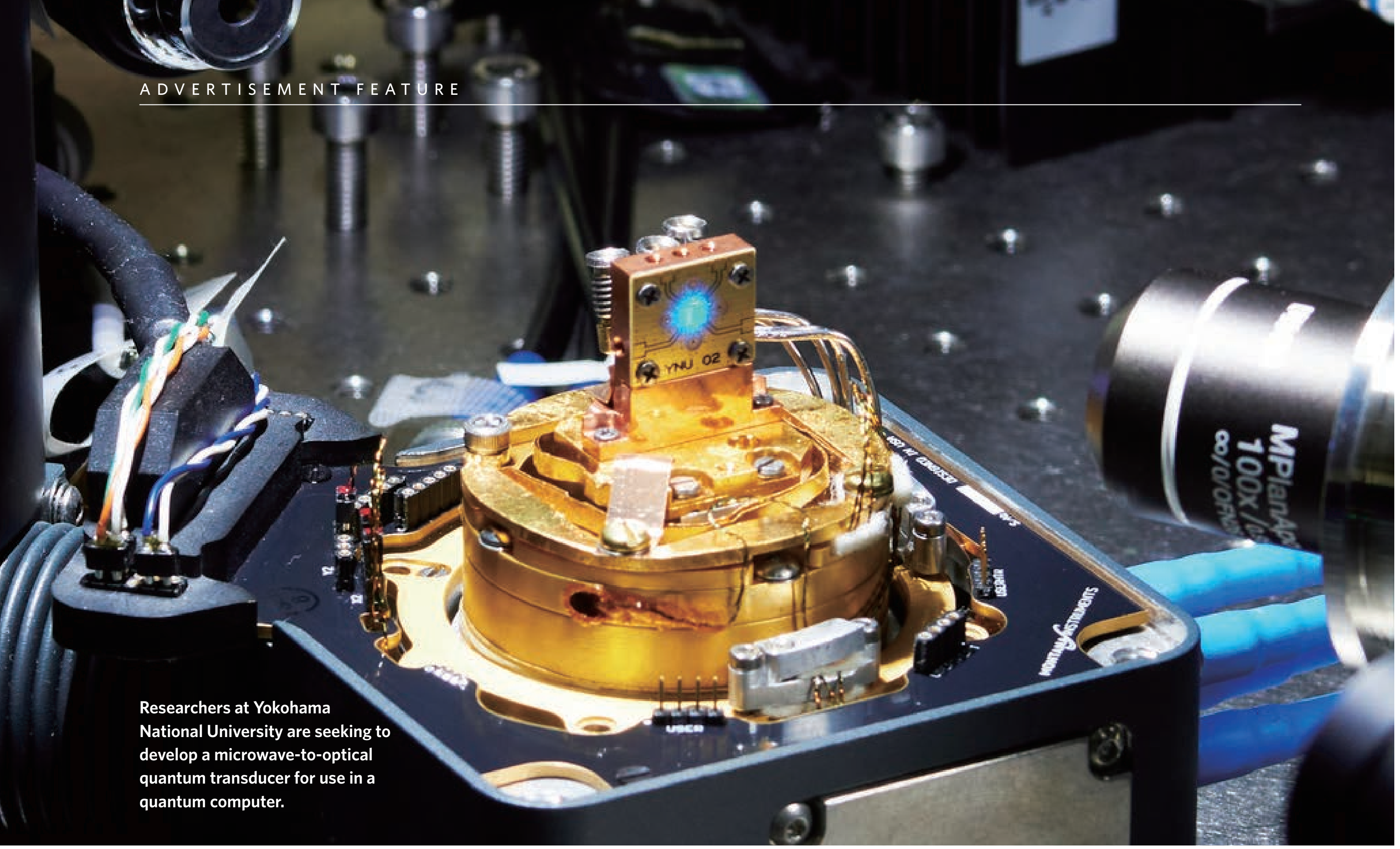

Researchers at Yokohama National University are seeking to develop a microwave-to-optical quantum transducer for use in a quantum computer.

USHERING IN A NEW ERA IN COMPUTING

The key components needed for universal quantum computers are BEING DEVELOPED IN THREE MAJOR PROJECTS IN JAPAN.

Quantum computers promise a revolution in computing power. By exploiting the properties of quantum states to process data, they can potentially perform complex calculations far beyond the reaches of conventional computers. They could find applications in diverse fields from medicine to materials design.

But quantum computers face some major hurdles before they become useful. For example, being based on fragile quantum states, quantum computers will require highly efficient error-correction mechanisms. To address these challenges, the Japanese government has launched a long-term initiative to develop fault-tolerant, universal quantum computers by 2050, called Moonshot Goal 6.

Three research projects led by Keio University, Osaka University and Yokohama National University are playing key roles in this Moonshot goal. They are constructing the basic components of quantum computers to store and process data; inventing new ways to connect these into larger systems; and developing the broader architecture to connect many quantum computers together into networks.

These quantum-computer networks could dramatically accelerate scientific discoveries, and perhaps lead to entirely new industries. “Conventional computing has limited computational power, whereas quantum computing has the potential to provide enormous computing power,” says Hideo Kosaka, who is the director of the Quantum Information Research Center at Yokohama National University, in Kanagawa prefecture, and who leads one of the Moonshot’s projects.

MANIPULATING QUBITS

In conventional computers, the basic unit of information is the bit, which can carry a value of either one or zero. In contrast, quantum computers depend on qubits, which can exist in two different quantum-mechanical states, such as the orientation of an electron’s spin or the polarization of a photon of light. Crucially, these qubits can exist in a superposition of both states simultaneously, and can connect to other quantum particles by a process known as entanglement. These two properties enable qubits to work together on fiendishly complicated calculations in ways that classical bits cannot.

One of the most promising types of qubits, first demonstrated by Japanese researchers in 1999, uses superconductors. These qubits typically encode data using a pair of superconducting electrons that can exist in two different states. Switching from one state to the other can trigger the superconducting qubit to emit a microwave photon.

Since this photon carries information about the qubit’s state, it offers a way to send data from one qubit to another. In practice, the microwave photon must first be converted into a photon of visible light so that it can be transmitted more easily. “Our goal is to connect remote superconducting qubits with optical fibres,” says Kosaka.

To achieve that, Kosaka’s team is developing a quantum transducer that converts microwave photons into optical photons without losing any quantum information. The transducer is based on a diamond with a defect in its structure, known as a nitrogen-vacancy centre. When a microwave photon hits the diamond, it generates vibrations in the crystal that alters the nitrogen-vacancy centre. An incoming optical photon then interacts with the nitrogen-vacancy centre, picks up the quantum information, and carries it away.

In principle, the quantum information could be stored inside the diamond for more than a minute without degrading, which may also make this technology useful as a short-term quantum memory system. Kosaka’s team is developing various other technologies to reduce the possibility of errors occurring within the system and to correct any errors that do occur.

BUILDING CONNECTIONS

Meanwhile, researchers are developing other kinds of qubits that rely on atoms, photons or semiconductor nanostructures known as quantum dots. Each of these could end up playing different roles within quantum computing systems — and they all need good connections.

“We’re working on the quantum networking technologies needed to connect and scale-up quantum computers based on all these qubits, including superconducting systems,” says Takashi Yamamoto, a deputy director of the Center for Quantum Information and Quantum Biology at Osaka University.

In a project led by Takashi Yamamoto of Osaka University, a team at the company Hamamatsu Photonics is developing a large-scale detector system that uses superconducting nanowires to measure single photons.

For example, atom-based qubits can be linked by using entangled photons to carry their information. To enable this, Yamamoto’s team has developed an atom-array-based quantum processor with photonic quantum interfaces and a superconducting nanowire single-photon detector system that can measure photons with extremely high efficiency and very low noise. Such a detector system can also be used to connect superconducting qubits with quantum interfaces developed in Yamamoto’s project.

The researchers are also developing a photon-networking technology based on nanofibres, which could manage a series of quantum-entangled photon qubits. One goal of this system is to ensure that the photon qubits maintain their quantum properties even at room temperature.

Semiconductor qubits carry information in the spin of an electron within the material, and Yamamoto’s project is exploring different ways to transfer this information. One approach involves a process called adiabatic quantum-state transfer, which could move information along a line of quantum dots. “We can transfer the quantum state from one qubit to the next, so that it moves from one end to the other,” Yamamoto says.

Yamamoto hopes some of these devices will be used in small-scale quantum computer networks in the next few years. “The next big challenge is to connect quantum computers by using our networking technologies,” he says. “That will be a crucial step.”

SPANNING THE WORLD

For quantum computers to reach their full potential, they will eventually have to function at a much larger scale. A general-purpose quantum computer may require a million qubits, for example. This could be achieved by connecting many medium-sized quantum-computing modules that each contain thousands of qubits.

To achieve that, researchers must not only develop quantum hardware — they will also need to design the architecture of quantum computing networks, and develop protocols needed to make them run smoothly.

“We need a very efficient and smart architecture for quantum networking to achieve large-scale quantum computing. This is crucial in any distributed architecture of quantum computing and, hence, for the sustainable development of quantum computers,” says Shota Nagayama, who is a vice-head of the Quantum Internet Center at Keio University in Tokyo and is also affiliated with Mercari, Inc.

Conventional computer networks are designed so that each computer acts as a node within a complex web of connectivity. That design ensures that if one node breaks, the network can continue to function.

It is much harder to achieve that kind of network for quantum computers, not least because it can be difficult to create reliable backups of quantum information without altering it. But by 2030, Nagayama’s team aims to have built a small, but robust and scalable quantum-computer network containing at least three quantum-computer nodes and demonstrated it as a testbed.

Ultimately, Nagayama hopes that such networks will expand until they span the globe to create a ‘quantum internet’, whereby every quantum computer on Earth would be integrated into one global-scale quantum computer network, he adds. This would provide billions of users the opportunity to tap into the transformative power of quantum computing. ■

MOONSHOT
RESEARCH & DEVELOPMENT PROGRAM

www8.cao.go.jp/cstp/english/moonshot/top.html