Theme article in
WACQT newsletter #8, 2022

Conversion between microwaves and light

If several superconducting quantum processors are to be connected into a large quantum computer, one needs to find a way to efficiently convert between microwave and optical photons without losing any quantum information. A new research team is now being formed at Chalmers to solve this challenge.

Superconducting circuits, cooled to almost absolute zero temperature, are one of the most promising and developed hardware platforms for quantum information processing. In this approach, the qubits are controlled and read out using microwaves, which is advantageous as this is a frequency band in which very good control equipment is already available.

The downside is that microwave signals are quickly swamped by thermal noise when emerging to room temperature. High transmission losses further prevent their propagation over long distances. This is an obstacle to connecting several superconducting quantum processors, located in separate cooling units (dilution fridges), into one large quantum computer.

Optical light signals, on the contrary, are hardly affected at all by thermal noise at room temperature, and can travel hundreds of kilometres with very low losses in optical fibres. Therefore, it would be highly advantageous to be able to efficiently transfer the quantum information encoded in microwave photons to optical photons, and the other way around.

No device that can do this exists today, but an increasing number of research groups, in the US, Europe and elsewhere, are now working to solve the challenge. It is a difficult challenge as there is a five-orders-of-magnitude difference in frequency, energy and wavelength between microwave and optical photons.

“Also, the conversion device must not accidentally measure the quantum states passing through, as measurements cause quantum states involving superposition and entanglement to lose their coherence and thus collapse, which makes it even more difficult,” says Raphaël Van Laer, assistant professor at the Quantum technology division at Chalmers.

He was recruited to Chalmers in 2021 and is now building an interdisciplinary research team in photonics and quantum technologies. In addition to lab start-up funding from WACQT, he has also received a Starting Grant from the European Research Council (ERC).

Many possible routes

There are many different possible routes to achieve microwave-to-optical frequency conversion. Some examples are:

- **Electro-optic conversion** employs the nonlinear Pockels effect that occurs in certain crystal materials – changing the optical refractive index by an electric field – to directly interface optical and microwave signals. By positioning an optical cavity made from Pockels materials in the electric field of a microwave resonator, the optical and microwave modes can be coupled, providing strong nonlinearity for direct microwave-to-optical photon conversion.
- **Electro-optomechanical conversion** utilises sound as an intermediate step between microwaves and light. Phonons – the smallest quanta of sound – can be supported at microwave frequencies (gigahertz), while their wavelength matches that of optical photons. This results from the five-orders-of-magnitude difference in the speed of light relative to the speed of sound. During recent years, remarkable development in chip-scale electro- and

optomechanics has been achieved. Such devices are combined into hybrid devices where the conversion takes the path from electrical (microwave) to mechanical (phonon) to optical signals, and vice versa..

- **Magnon-mediated conversion** utilises magnons, that is the collective excitation of spins in magnetically ordered materials, for mediating microwave-to-optical photon interaction.
- **Atom-assisted conversion** incorporates various existing quantum technologies based on atoms and solid-state emitters. The microwave and optical fields are mixed in a closed loop of transitions in these emitters.

“I have worked in this field for some years and two routes seem most advanced to me: direct electro-optic conversion and electro-optomechanical conversion. But the jury is still out on which approach is to be most useful in the long run, and different types of converters could take on complementary roles,” says Van Laer.

Personally, he is currently most excited about the electro-optomechanical route.

“My former colleagues at Stanford University and I have done back-of-the-envelope calculations and measurements that seem very promising, and especially for the mechanical approach. This approach demands fundamentally less power than the direct electro-optical route.”

Obstacles to overcome

Power consumption is one of the main obstacles to handle when designing a microwave-to-optical converter. To be useful with superconducting quantum processors, the device must be placed inside the dilution refrigerator that houses the processor chip at a temperature of a few tens of millikelvins above absolute zero.

“At these low temperatures, one can only dissipate of order 10 microwatts of power before the fridge starts heating up, and we cannot even use all of it for the microwave-to-optical conversion,” Van Laer explains.

Another challenge is the efficiency of the device. For each microwave photon sent in, an optical photon should preferably come out – that is, a quantum conversion efficiency close to 100 percent. Most devices demonstrated so far have an efficiency of below one percent. A third aspect is noise – the device should not add any noise to the quantum information coded in the photons. And a fourth is that the optical photons should not damage the sensitive superconducting circuit with their high energies.

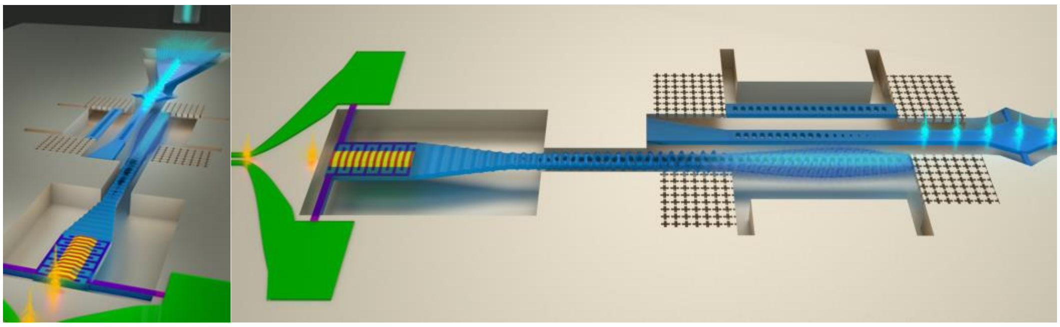
“These are general device requirements. An extra constraint that we put on ourselves is that we want to use methods that make the manufacturing and development of the device scalable, ideally fully compatible with those used in the semiconductor industry.”

Fail quickly and learn

Van Laer is now building up his laboratory at Chalmers. The renovations of the rooms are about to finish, and then the group will start to install equipment. A dilution fridge has been procured and should be delivered at latest by the summer.

Initially, the group plans to focus on electro-optomechanical conversion. Part of the idea is to integrate the best properties of two materials in a hybrid platform: thin-film silicon which is strongly photoelastic, and thin-film lithium niobate which is strongly piezoelectric.

“I don’t think it is possible to figure out exactly how the device should be designed or operated in advance. Instead, we will set up a cyclic process where we iterate from designing a device, to fabricating it in Chalmers’ nanofabrication laboratory and then measuring it both at room temperature and cryogenic temperature. The plan is to fail quickly and learn from that,” says Van Laer.



Artist impressions of a device converting between microwave (yellow) and optical photons (blue) via gigahertz sound. The superconducting circuit is not shown. This is one example from a vast design space. Credit: R. Van Laer

He also plans to work with the superconducting qubit experts at Chalmers, such as Simone Gasparinetti, to figure out how the device could operate well together with the qubits. WACQT director Per Delsing's pioneering work on quantum acoustics (read more) is also something to learn from when designing the phonon part of the conversion device. In addition, the Photonics division at Chalmers, led by Peter Andrekson, has much related expertise on classical opto-electronic systems which the team may benefit from.

"I have also been very lucky to have done my postdoctoral research as part of an amazing team led by Amir Safavi-Naeini at Stanford working on this and related topics. We are keeping in touch. These are huge challenges, and it will likely require global collaboration to truly address them – similar to what happened with transistor technology and the internet over decades."

The research field of quantum microwave-to-optical conversion is still at an early stage. A group in Colorado has demonstrated a converter that has an efficiency approaching 50 percent, which is impressive, but the device still adds too much noise to convert quantum signals and has low scalability.

"No one has been able to do even the basic science demonstrations yet, for example optically generating entanglement between microwave devices located in two separate dilution fridges. We hope to do some of these fundamental science experiments in the coming years," says Van Laer.

Applications in both quantum and classical technology

If the research community succeeds in building an efficient microwave-to-optical converter, the field of applications will not be limited to connecting superconducting quantum processors.

"Humanity has never had this kind of device. We have worked a lot with microwaves and a lot with optics, but we have not coherently and efficiently interconnected the two domains. This is a very general scientific challenge, with possible applications in classical technologies and in quantum technologies beyond those using superconducting qubits."

Within quantum computing, Van Laer thinks that a microwave-to-optical converter could be useful also with hardware based on optically addressable atoms or ions with long lifetimes. It may also lead to new architectures which combine superconducting and optical quantum processor architectures.

"The methods needed to build quantum microwave-to-optical converters would also enable very good classical devices. For example, these may be used to reduce the power consumption in many situations involving data transmission, such as in data centres, smartphones, and autonomous systems like self-driving cars. I am excited that this research connects with so many interesting topics at once, and Chalmers and WACQT are some of the finest environments to explore all of this," says Van Laer.

Text: Ingela Roos

Further reading

Microwave-optical quantum frequency conversion (review article in Optica)
Efficient bidirectional piezo-optomechanical transduction between microwave and optical frequency (Nature Communications)
Controlling phonons and photons at the wavelength scale: integrated photonics meets integrated phononics
(review article in Optica)
Superconducting qubit to optical photon transduction (Nature)
Harnessing electro-optic correlations in an efficient mechanical converter (Nature Physics)