LITHIUM NIOBATE ON INSULATOR
FROM CLASSICAL TO QUANTUM PHOTONIC DEVICES

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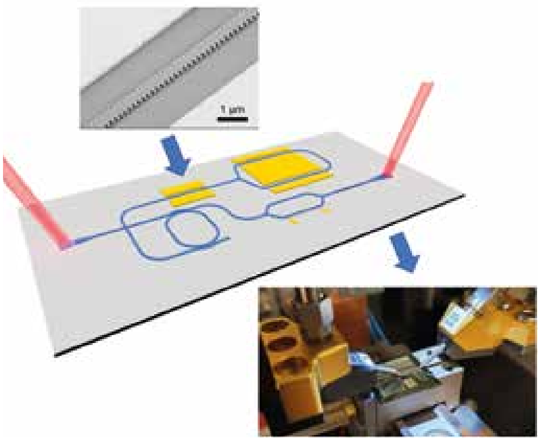

Integrated photonics is becoming more and more multifunctional thanks to the recent availability of an established material, lithium niobate, as thin films of less than 1 micron thickness. Overcoming key fabrication challenges has put this platform on its way to achieve scalability. Here, we show the performances of integrated and free space devices such as electro-optic modulators and active metasurfaces. Finally, we mention possible roles of lithium niobate on insulator in quantum photonics.

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Who could have guessed the great evolution of lithium niobate in applied research, a bulk material already extensively used in telecommunications and lasers? This time, it made a sensational appearance in integrated optics thanks to two technological developments: thin film fabrication at wafer scale and nanolithography beyond the typical semiconductor processes. The pressing necessity to reduce power consumption and footprints in the data transport industry either in submarine fibres or data centre networks was a breeding ground for innovative integrated solutions with more functionalities.

Lithium niobate ($LiNbO_3$) is a synthetic crystal, transparent from the ultraviolet to the mid-infrared, that lacks inversion symmetry and displays ferroelectricity, the Pockels effect, the piezoelectric effect, photoelasticity and nonlinear optical polarizability. It is only in the early 2000's that lithium niobate was fabricated on a thin film platform and less than 10 years ago that it was made commercially available as lithium niobate on an insulator (LNOI) [1].

Similar to the silicon-on-insulator (SOI) platform, the combination of a high refractive index material ($n > 2$) and a thickness of less than 1 µm, bonded to an insulator layer, increases the optical mode confinement with waveguide cross-sections. As illustrated in Fig. 1, waveguides with cross-sectional areas less 1 µm^2 waveguide can be fabricated by electron-beam lithography in thin film lithium niobate, which allows for much stronger light confinement than in waveguides generated by *e.g.* titanium indiffusion or micromechanical processes [2].

A broad portfolio of optical devices has been created in the SOI platform,

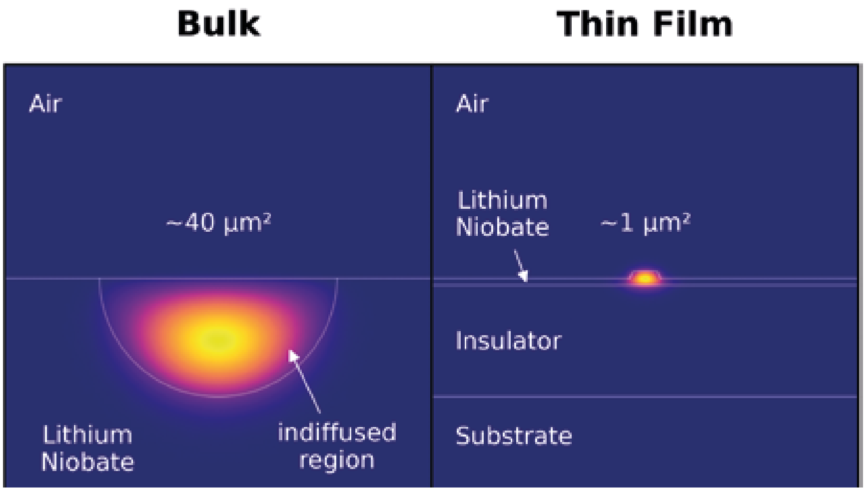


Figure 1. Cross-sections of typical waveguides for bulk (left) and thin film (right) lithium niobate. The color bar shows the intensity of the propagating optical mode. Its mode volume is reduced by one order of magnitude for ridge waveguides as compared to indiffused waveguides.

from on chip lasers to optical modulators and waveguide-integrated photodetectors. Silicon nitride is also worth mentioning since it has low propagation losses and a wider transparency range than silicon. These two thin-film platforms offer high mode confinements where the waveguide dispersion can overcome the normal material dispersion by engineering the device parameters. However, silicon and silicon nitride do not exhibit second-order nonlinearities, thus only few nonlinear optical effects such as self-phase modulation, third-harmonic generation, or four-wave mixing can be exploited. Besides the fabrication of photonic integrated •••

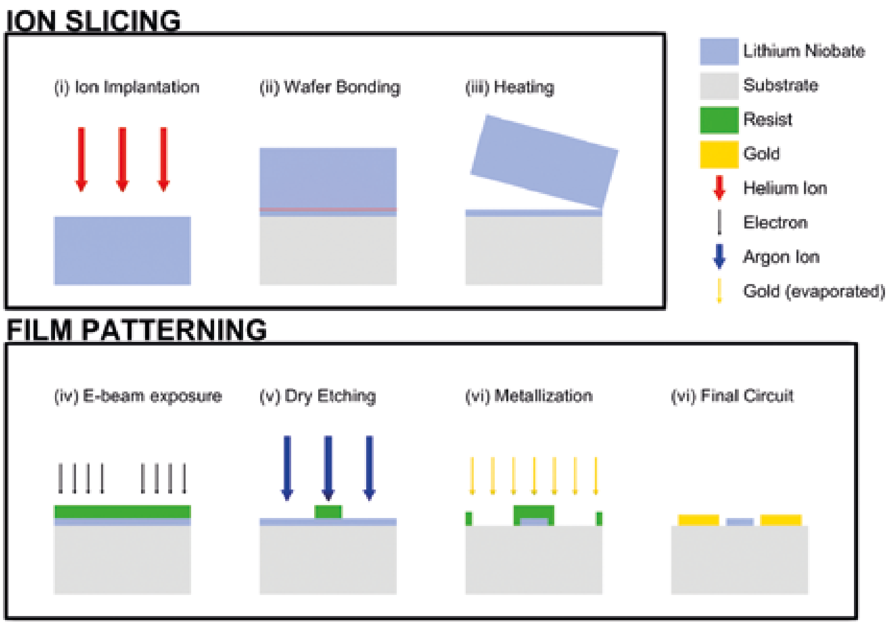


Figure 2. Typical steps required to fabricate a LNOI integrated circuit. Ion slicing (i) - (iii) is used to produce lithium niobate-on-insulator wafers. Thin films are patterned using electron-beam lithography (iv) and dry etching (v). If required, subsequent lithography steps are used to add metallization layers (vi) for electrodes. Finally, the patterned chip has to be cleaned to get the final integrated circuit (vi).

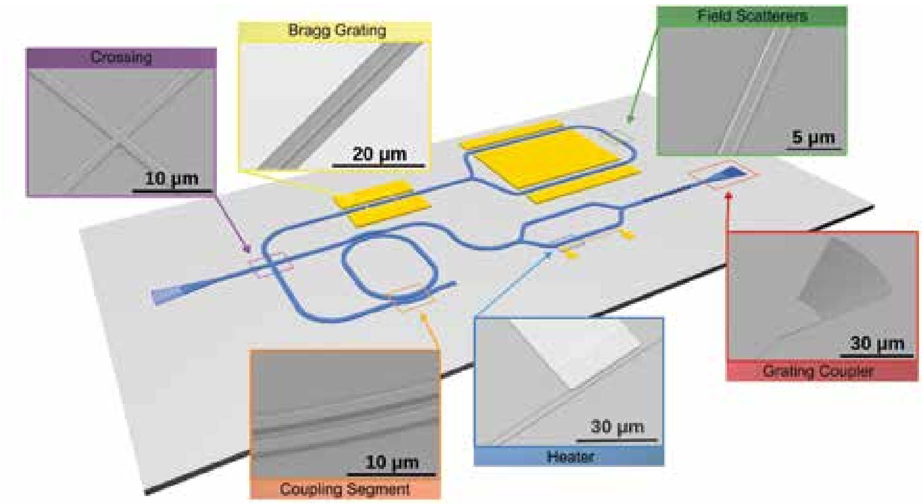


Figure 3. An example of a lithium niobate-on-insulator photonic chip with various functionalities showing the fabrication capabilities with inset scanning electron microscope images.

circuits in lithium niobate thin film, we will mention free space applications using lithium niobate as a metasurface for electro-optic modulation and quantum light sources.

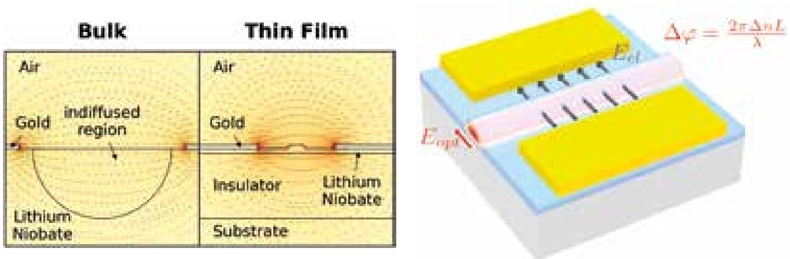
NANO-FABRICATION

Crucially, the miniaturization of lithium niobate waveguides was enabled by the ion slicing process described in Fig. 2. By implanting helium ions into the crystal matrix of lithium niobate at a depth controlled by the ion energy, thin layers of lithium niobate can be split-off. To make these layers usable, the implanted lithium niobate wafer is bonded to a substrate. Different kinds of substrates such as silicon, quartz or sapphire, and possibly an insulation layer, can be used depending on the application. These thin film wafers are commercially available and serve as base for further nanofabrication.

The nano-structuring is based on similar approaches as for silicon or silicon nitride waveguides as described in Fig. 2. However, lithium niobate is a notoriously hard material to etch, and thus requires specialized tools and processes. First, the desired waveguide circuit is patterned into a photosensitive resist using an electron beam, which allows features sizes smaller than 1 µm. The patterned chip is then etched using argon ions in an inductively coupled plasma etching tool. To exploit the electro-optical properties of lithium niobate (see box "Electro-optic effect"), metal electrodes are routinely added by patterning a resist and then depositing metal via chemical vapor deposition.

Using this fabrication process, many different structures can be realized. Fig. 3 shows scanning electron microscope images of several components used to build a photonic integrated circuit showing the capabilities of the fabrication methods. The high precision of electron beam lithography enables fabrication of crossing waveguides and narrow gaps (down to 200 nm) which are crucial for general routing, grating couplers and integrated microresonator coupling. Recently, Joule heaters made of platinum with gold contacts deposited next to an optical waveguide were achieved and allow for a fine tuning of the properties of a photonic chip without additional fabrication [3]. Lastly, electron beam lithography also enables fabrication of metal nanowires with feature sizes below 100 nm. Such strips can be used as scatterers to probe the optical field inside ● ● ●

ELECTRO-OPTIC EFFECT



The linear electro-optic effect present in materials with high second-order nonlinearities is a response to an externally applied electric field. Due to this field, the refractive index of the material changes by an amount Δn, leading to a change of the phase light traveling in the material accumulates. Notably this phase change Δφ depends both on the orientation of the applied electric field and the polarization of light. In the case of integrated lithium niobate devices, the electric field is typically introduced by placing gold electrodes in close proximity to waveguides. In lithium niobate-on-insulator, higher electric fields can be achieved due to the reduction of the electrode gap as compared to waveguides in bulk lithium niobate. Furthermore, for ridge waveguides the electric field is better aligned to the extraordinary crystal axis, whereas for buried waveguides in bulk lithium niobate there are always components in multiple directions.

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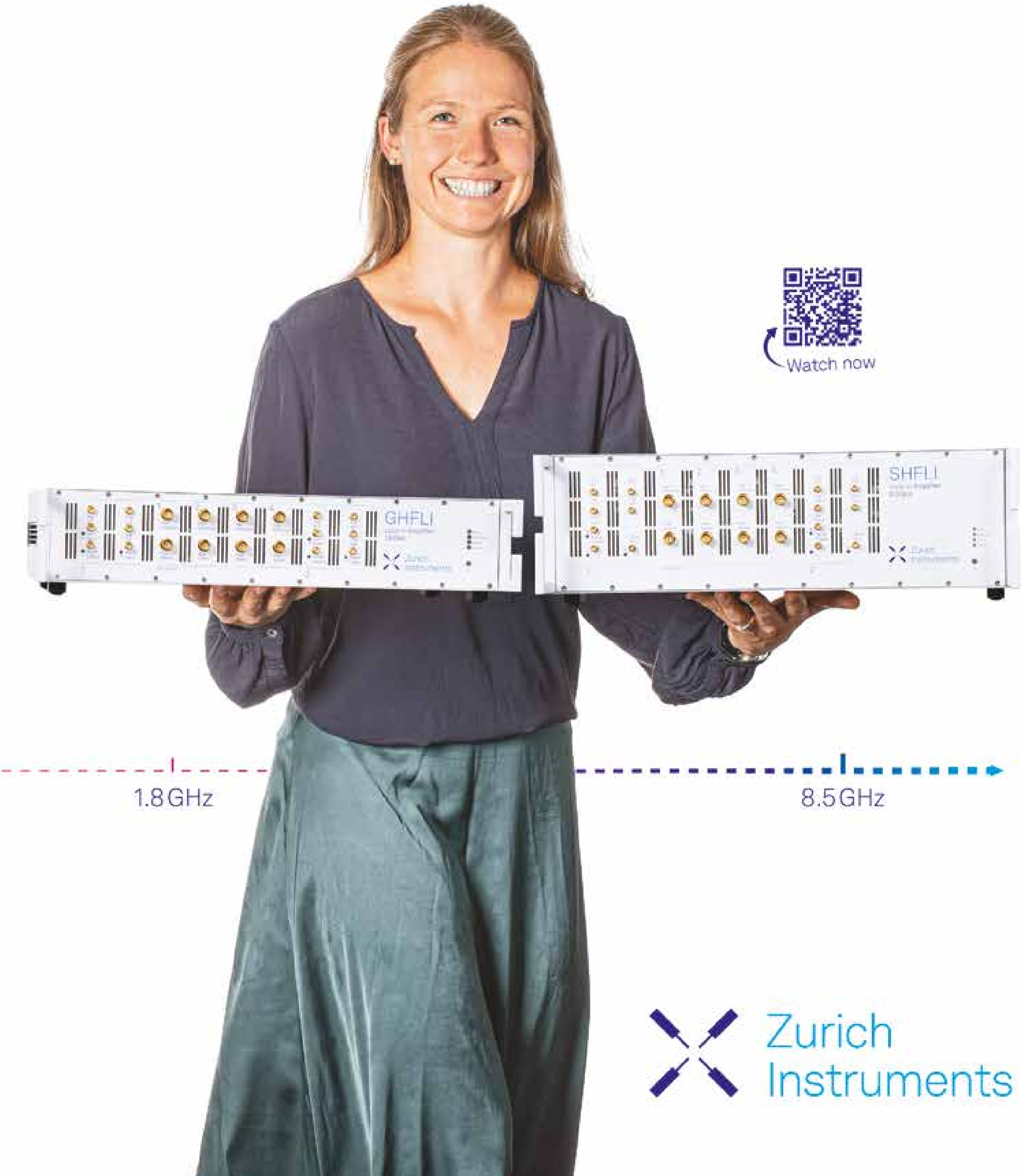

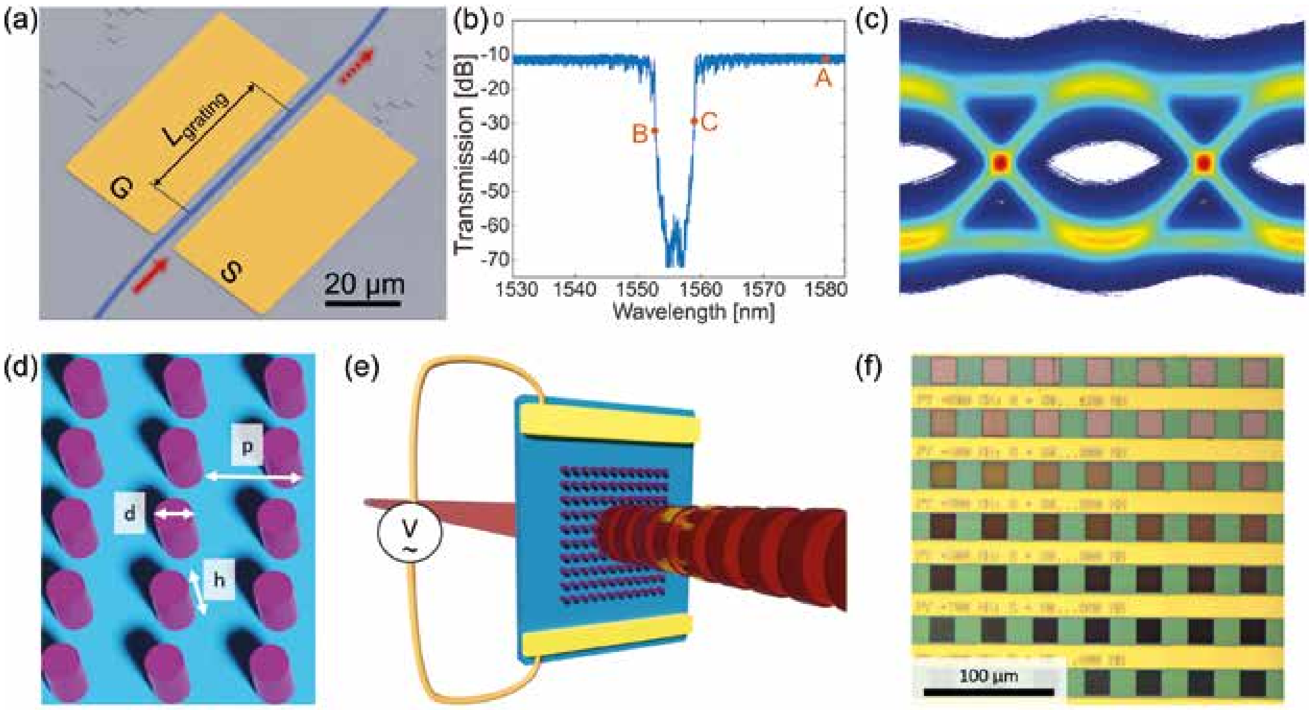

Figure 4. Lithium Niobate Devices. a) False-colored electron microscope image of a Bragg grating modulator. b) Wavelength dependent transmission of Bragg modulator showing the characteristic stopband. c) Eye diagram of a 100 GBit/s signal transmitted by the modulator. d) Sketch of lithium niobate pillars arranged into a periodic array to form a metasurface. e) Sketch of a LN metasurface composed of pillars, which, by applying a voltage, modulates a transmitted laser beam. f) Optical image of a fabricated set of metasurfaces with changing radii and periods, where the colors directly show the different resonance wavelengths. (Adapted from Pohl *et al.* IEEE Photonics Technology Letters **33**(2), 85 (2021), and Weigand *et al.* ACS Photonics **8**(10), 3004 (2021))

waveguides. This concept was exploited in monolithically integrated spectrometers [4]. The effort to scale the fabrication of the substrate and of devices to commercially relevant amount experiences a major push in Europe currently [5].

ELECTRO-OPTIC DEVICES

Due to the electro-optic effect (see box "Electro-optic effect") lithium niobate is primarily used for active, tunable or reconfigurable devices. Today, electro-optic modulators using bulk lithium niobate are available in many research labs, telecommunication networks, or satellites. With the miniaturization of integrated circuits enabled by electron-beam fabrication, smaller and more efficient devices can be realized with lithium niobate-on-insulator. Typical low power consumption electro-optic modulators use a Mach-Zehnder interferometer [6]. For an even smaller footprint, single waveguides with an integrated Bragg grating, shown in Fig. 4(a), was realised. It features a stopband with sharp slopes (see Fig. 4(b)), which can be shifted by applying an electric field. At suitable wavelengths (points B or C in Fig. 4(b)), the transmitted light is either fully transmitted or fully blocked depending on the applied electric field. This principle is used to translate an electronic stream of bits into the optical domain, where it can be transmitted through optical fibres. Fig. 4(c) shows a characteristic eye diagram of a 100 GBit/s signal showing high quality data transmission through an optical fibre.

Besides integrated photonics, thin film lithium niobate is also suited for free space applications such as electro-optic metasurfaces (Fig. 4 d-f), which provide a tool to modulate light that passes perpendicular through the surface, hence circumventing the problem of coupling light to the tiny cross-section of a waveguide. Metasurfaces consist of a periodic 2-dimensional array of nanoscale resonators and can be scaled to an arbitrary size (see Fig. 4d). The small resonators can serve mainly two purposes. The first idea is to engineer the phase of the transmitted light spatially and therefore replacing a plethora of optical elements for wavefront shaping such as lenses or beam deflectors with a thin-film alternative. The second purpose is to confine the light inside the structured material and therefore enhance the light-matter-interaction. Boosting *e.g.* the frequency conversion for second-harmonic-generation or spontaneous parametric down conversion is especially useful since phase matching is not occurring in sub-wavelength interaction lengths, hence avoiding the need of periodic poling of the lithium niobate. This efficiency boost opens the path towards active flat optical devices exploiting the Pockels effect for faster pixel switching than spatial light modulators based on liquid crystals. Recently we showed that by structuring nanoscale pillars in a lithium niobate thin-film, a precisely chosen resonance can increase the modulation efficiency by a factor of 80 compared to an unpatterned thin-film (see Fig. 4(e)) [8]. The modulation voltage was kept below 10V, having therefore a comparable power consumption to the integrated modulators. Even though the modulation amplitude is still far from the optimized integrated photonics counterpart, this work shows the potential of combining metastructures with nonlinear thin-films like lithium niobate without the need for packaging since it all happens in free space (see Fig. 4(f)).

A FUTURE IN QUANTUM OPTICS

We have highlighted the development of nano-fabrication methods for patterning lithium niobate films and how it has led to a fast development of miniaturized devices for integrated circuit and compact free space optics. In light of the ever-increasing demand for small scale solutions for quantum technology, lithium niobate-on-insulator is very promising as classical integrated high dynamic range modulator for atom traps, or as entangled on-chip photon sources through spontaneous parametric down conversion [7]. Compared to silicon photonics and other semiconductor materials, lithium niobate does not suffer from two-photon absorption, which limits the efficiency of logical quantum gates. Therefore, the story of this material is about to open a new chapter.

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