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# Wireless Millimeter-Wave Electro-Optic Modulators on Thin-Film Lithium Niobate

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**Abstract:** We present a wireless electro-optical modulator based on a thin-film lithium niobate operating at a millimeter-wave frequency range of 80–380 GHz, where the wireless signals are coupled to the on-chip transmission line directly from free space via a large aperture antenna. ©2025 The Author(s)

## Introduction

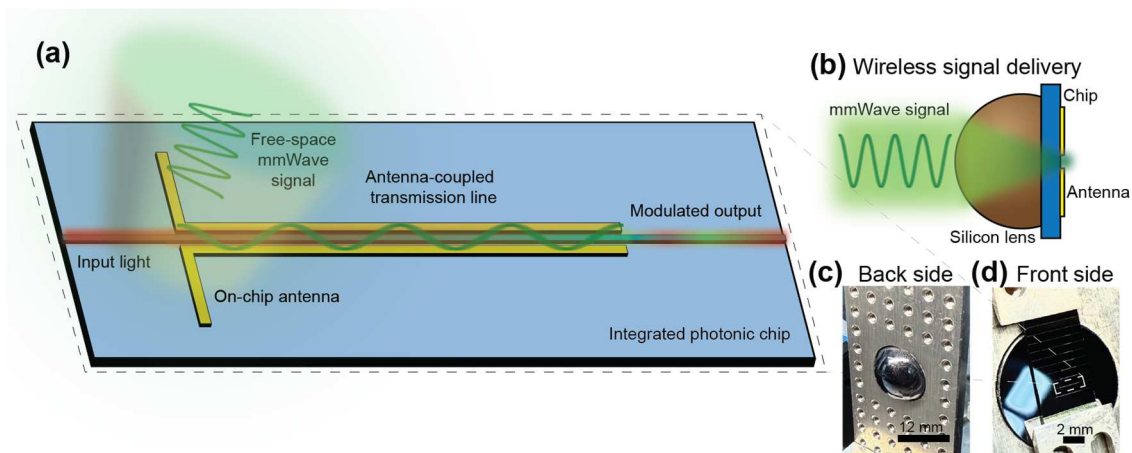
Electro-optic modulators (EOMs) operating in the millimeter-wave (30–300 gigahertz) and terahertz (0.3–10 terahertz) frequency ranges are key components in modern communication [1] and sensing systems [2]. Recent advances in EOMs with bandwidths reaching up to 1 terahertz [3] promise to dramatically increase data transmission rates while reducing energy consumption—an especially compelling prospect given the growing demands of data centers and the rapid development of artificial intelligence models.

Modern EOM designs typically require millimeter-wave (mmWave) and terahertz signals to be delivered via fragile and complex ground-signal-ground probes [4, 5]. Moreover, coaxial cables become increasingly lossy above 100 GHz, often necessitating the use of bulky and inflexible rectangular waveguides. These limitations

pose significant challenges, particularly in applications such as radar systems, which are incompatible with conventional high-frequency signal delivery schemes.

To address these issues, recent research has turned to on-chip antennas that couple free-space mmWave and terahertz signals directly into on-chip transmission lines. However, existing demonstrations have so far been limited to operating frequencies below 60 GHz [6–8].

In this work, we overcome these limitations by employing hybrid mmWave–optical integrated photonic circuits based on thin-film lithium niobate (TFLN)—a material platform that has gained significant attention for enabling integrated terahertz photonics [9, 10]. TFLN allows the realization of large-area integrated circuits for terahertz electro-optic detection, beam profiling [11] and broadband terahertz generation [12]. The modulation efficiency can be optimized by engineering the geometry of the transmission



**Fig. 1:** Wireless electro-optic modulator (EOM) in thin-film lithium niobate. (a) A conceptual sketch of a wireless EOM, where a millimeter-wave (mmWave) signal is coupled to the transmission line via the on-chip antenna and modulates the phase of the waveguided optical probe. (b) A sketch of the wireless signal delivery scheme, where the mmWave signal is focused by a silicon lens. A photograph of the back (c) and front (d) sides of the chip mounted in the holder.

line electrodes surrounding the optical waveguide. The transmission line is terminated with an on-chip antenna, which wirelessly couples the incoming signals from free space directly to the chip.

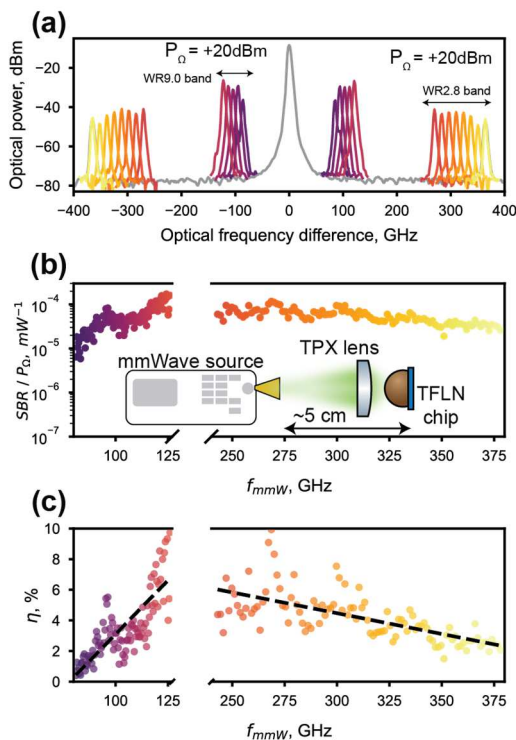
In this paper, we demonstrate the performance of wireless EOMs based on the TFLN platform in the frequency range of 80–380 GHz and report a free-space-to-chip coupling efficiency of up to 10%.

### Operating principle of wireless electro-optic modulators

A sketch of the proposed device is presented in Fig. 1(a). An on-chip antenna couples mmWave radiation from the free space and launches it into the transmission line, which is placed around the optical waveguide. However, the voltage generated by the antenna for a given free space electric field depends on its geometrical dimensions. In addition, we use a silicon lens attached to the back of the chip and aligned with the center of the antenna to focus the mmWave radiation on the antenna, enhancing the amount of voltage generated, as shown in Fig. 1(b)-(d). The coupled mmWave radiation modulates the phase of an optical wave through the electro-optic effect, generating sidebands in the frequency domain.

## Results

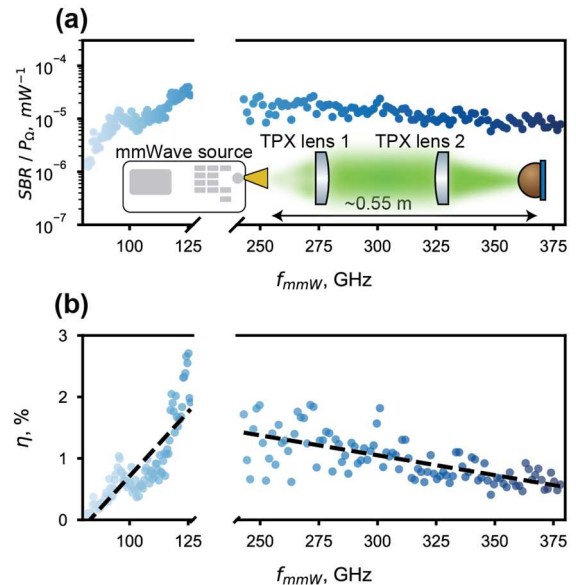
We terminated the dipole antenna (200  $\mu\text{m}$  half-arm length) with a 2 mm-long transmission line, and pumped the photonic chip with a



**Fig. 2:** Experimental results. (a) The measured output spectra for various frequencies of mmWave radiation, (b) sideband ratio per mW of mmWave power and (c) coupling efficiency for various frequencies.

continuous-wave laser at 1550 nm. We achieved -9 dB coupling efficiency per facet by using optical lensed fibers. We generated the mmWave radiation using the frequency multiplier chain, which allows us to generate the mmWave radiation in the 82-125 GHz range and 240-380 GHz. The generated radiation was then emitted into the free space via a horn antenna.

We measured the spectrum of the output optical radiation. We swept the mmWave frequency  $f_{mmW}$  and found a sideband ratio ( $SBR$ ) of approximately -20 dB at 100 GHz, with a corresponding +20 dBm of free-space mmWave power  $P_{\Omega}$ , and of -35 dB at 300 GHz, with a corresponding mmWave power of +5 dBm, as shown in Fig. 2(a). To make a conclusion about the frequency response of the device, we plotted the sideband ratio per mW of mmWave power  $P_{\Omega}$  and observed an increasing response with frequency in the 82-125 GHz range, and a decreasing trend at frequencies of 240-380 GHz, as presented in Fig. 2(b). As described in the Methods section, we extracted the coupling efficiency and plotted it as a function of the mmWave frequency in Fig. 2(c). We fitted the coupling efficiency with a linear function. We attributed these trends to the spectral response of the horn antenna, namely to the frequency-dependent Gaussian beam waist emitted by the



**Fig. 3:** Experimental results for the configuration in which the chip is positioned at a distance of 0.55 m from the millimeter-wave source, demonstrating effective remote wireless coupling (a) Sideband ratio per mW of mmWave power and (b) coupling efficiency for various frequencies. The scale in (a) is kept consistent with Fig. 2(b) for direct comparison.

antenna.

Further, we investigated the scenario where the mmWave source is located at a distance

(~0.55 m) from the chip to mimic a real-life usage case, e.g. in 6G communication. In this scenario, we used two TPX lenses, one to collimate the output radiation from the source and the second to focus the wireless signal on the chip. We swept the frequencies and plotted the normalized *SBR* per  $P_\Omega$  (Fig. 3(a)) and demonstrated the coupling efficiency up to 3% in this configuration, as plotted in Fig. 3(b).

## Conclusions

We have experimentally demonstrated a wireless electro-optic modulator operating in the millimeter-wave frequency range of 80–380 GHz, implemented on a thin-film lithium niobate (TFLN) photonic integrated circuit. This work highlights the potential of integrating high-frequency wireless signal reception with low-loss, high-bandwidth optical modulation on a compact chip-scale platform. By eliminating the need for traditional bulky and lossy interconnects such as waveguides and coaxial cables, our approach enables a more scalable and versatile solution for future photonic systems.

This demonstration represents a significant step toward practical terahertz and millimeter-wave wireless photonic systems, which have promising applications in advanced radar, remote sensing, non-invasive imaging, and high-capacity wireless communication. Moreover, the compatibility of our platform with scalable fabrication processes opens new pathways for mass-manufacturable terahertz photonic chips for next-generation integrated systems.

## Methods

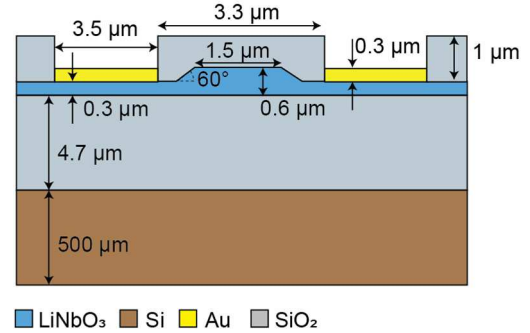
The sideband ratio characterizes the performance of the EOMs. We derived that the *SBR* is given by:

$$SBR = \frac{(\chi_{333}^{(2)} \cdot \omega_o)^2 \Gamma_{eo}^2 L^2 PM^2}{2 n_o n_\Omega c^3 \varepsilon_0 S_\Omega} \cdot \eta P_\Omega \quad (1)$$

where  $\chi_{333}^2 \approx 360 \frac{pm}{V}$  is a nonlinear second-order susceptibility of the lithium niobate,  $\omega_o$  is the angular frequency of the optical probe,  $\Gamma_{eo}$  is an overlap factor between optical and mmWave modes, defined as in [12],  $L$  is the length of the transmission line,  $PM = \left| \frac{e^{i\Delta k L} - 1}{\Delta k L} \right|$  with wave vector mismatch  $\Delta k = \frac{\Omega}{c} (n_\Omega - n_g) + i \frac{\alpha_\Omega}{2}$ , where  $n_\Omega$  is the mmWave mode effective index,  $n_g$  is the group index of the optical mode,  $\alpha_\Omega$  is the propagation loss of the mmWave radiation,  $\Omega = 2\pi f_{mmW}$  is the angular frequency of the mmWave radiation,  $n_o$  is an effective optical re-

fractive index,  $c$  is the speed of light in a vacuum,  $\varepsilon_0$  is the vacuum permittivity,  $S_\Omega$  is an effective mode area,  $\eta$  is the coupling efficiency of free-space mmWave radiation into the transmission line. Using eq. (1), we extracted the coupling efficiency  $\eta$ .

The parameters of the optical waveguide ( $n_g$



**Fig. 4:** The detailed sketch of the optical waveguide and transmission line.

and  $n_o$ ), and of the transmission line ( $n_\Omega$ ,  $S_\Omega$  and  $\alpha_\Omega$ ) were simulated using CST Studio Suite. The structure details are provided in Fig. 4.

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