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# High-Speed Wireless Terahertz Electro-Optic Modulators on Thin-Film Lithium Niobate

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**Abstract:** We present a compact high-speed electro-optical modulator based on a thin-film lithium niobate platform for continuous-wave wireless-to-optical signal conversion, which collects terahertz signals between 82-380 GHz directly from free space via a large aperture on-chip antenna. © 2024 The Author(s)

## 1. Introduction

The terahertz (THz) frequency range, spanning from 0.1 to 10 THz, holds immense potential for applications such as next-generation 6G communication systems [1], imaging systems [2], and non-destructive security screening [2]. Efficient detection of continuous-wave THz wireless signals with high signal-to-noise ratios is crucial for unlocking these applications, as it enables reliable operation in scenarios ranging from ultra-fast data transfer to high-resolution imaging. However, achieving such detection with high speed and precision remains a significant challenge in this frequency range.

The nonlinear mixing of THz and optical radiation is a well-established and powerful toolbox for THz detection [3]. Such techniques such as electro-optic sampling, allow low-noise measurements of the free space THz radiation. However, the standard electro-optic sampling suffers from three main challenges: (i) the need to tightly focus the THz beam onto nonlinear crystals, (ii) the limited availability of nonlinear crystals that support phase matching between THz and optical probe over a broad bandwidth, and (iii) its compatibility only with phase-locked THz pulses, making it unsuitable for detecting continuous-wave or free-running signals that are prevalent in communication systems [4].

To overcome these challenges, we leverage hybrid THz-optical integrated photonics circuits in thin-film lithium niobate (TFLN), which offer the key advantage of dispersion engineering [5, 6]. By placing the metallic electrodes of a THz transmission line around the optical waveguide, the propagation velocity of the THz and optical modes can be fine-tuned. This can be achieved by adjusting the electrode and waveguide geometry.

Prior work has successfully demonstrated the potential of this approach for broadband THz emission and quasi-phase-matched THz detection, particularly showcasing its effectiveness only with pulsed THz radiation [4]. In this work, we conceptualize, implement and demonstrate high-speed electro-optic modulators specifically designed for continuous-wave THz wireless systems. Unlike conventional guided-wave modulators that rely on radio-frequency (RF) signals delivered via RF cables—requiring impedance matching to the standard  $50\Omega$  often at the expense of overlap or coherence length—our approach couples THz radiation directly from free space through a custom-designed antenna. This innovation not only eliminates the constraints of cable-based impedance matching but also allows for greater design flexibility in the THz transmission line, optimizing the efficiency of nonlinear mixing. The antenna, in this context, acts as both a signal generator producing a voltage  $V_{ant}$  and impedance source of  $Z_{ant}$  enabling a novel, highly efficient interaction between THz and optical fields.

## 2. Results.

The sketch of the proposed device is presented in Fig.1(a). An on-chip antenna couples THz radiation from the free space and launches it into the transmission line, which is placed around the optical waveguide. The THz radiation modulates the phase of an optical wave, resulting in the sideband generation in the frequency domain. The ratio of the sideband to the optical carrier is proportional to the power of coupled THz radiation. Fig. 1(b) shows a photograph of the fabricated device. The equivalent circuit of the device is shown in Fig. 1(c), where the antenna acts as the voltage source, launching the THz radiation into the transmission line. However, the voltage generated by the antenna for a given free space THz electric field depends on its geometrical dimensions. We simulated the antenna performance using CST Studio and calculated the coupling efficiency, which is defined as the power of THz coupled into the transmission line radiation relative to the incident THz power. The results are shown in Fig.2(a). As expected, the peak of the coupling efficiency for longer lengths of the dipole antenna shifts towards shorter frequencies. Based on

our simulations, we chose the length of the dipole antenna to be 400 microns, as it covers the largest bandwidth in the frequency range of 100-400 GHz.

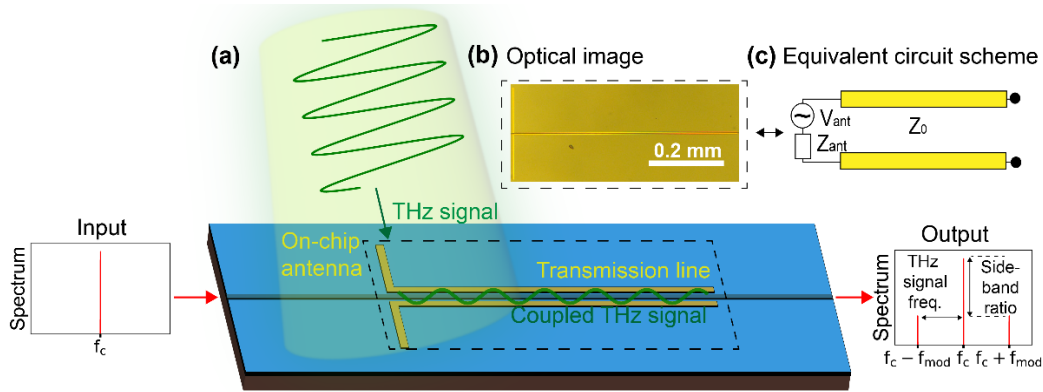


Fig. 1. (a) Device schematic. (b) Optical image of the device. (c) Equivalent electrical circuit of the device.

We measured the fabricated devices combining the antenna with a 1 mm transmission line (Fig. 2(b)). Under THz radiation, the optical probe was modulated, and the sidebands (colored lines, left axis) recorded via an optical spectrum analyzer together with the input THz power (green, right axis). We find a sideband ratio of approximately -30 dB at 100 GHz, corresponding to 100 mW of sub-THz power, and of -42 dB at 350 GHz, corresponding to 1 mW of THz power. The absolute values of the sidebands follow the power of the THz source in the entire range, demonstrating a modulator bandwidth of 380 GHz, limited by our experimental setup. Another metric, that quantifies modulation efficiency, is conversion efficiency  $\eta_{conv} = \frac{P_{SB}}{P_{cr}} \cdot \frac{1}{I_{THz}}$  where  $P_{SB}$  is the power of the generated sideband,  $P_{cr}$  is the carrier power, and  $I_{THz}$  is the intensity of THz radiation illuminating the device. The theoretical values of the conversion efficiency fit well with the measured ones, as it is shown in Fig.2(c).

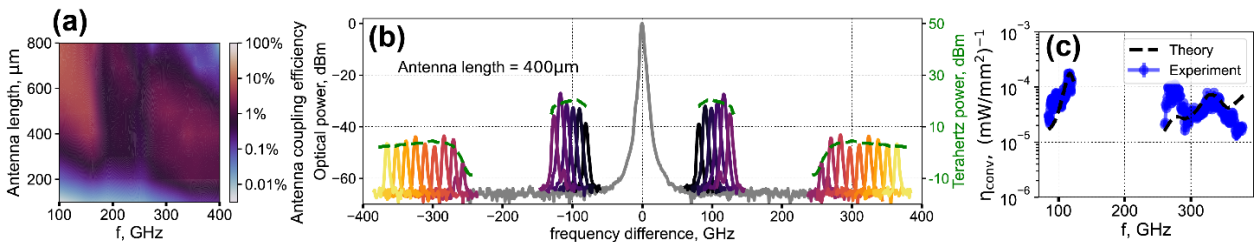


Fig. 2. (a) The simulated coupling efficiency of the THz radiation by the dipole antenna. (b) The measured modulated optical signals at two THz frequency ranges: 82-125 GHz and 250-380 GHz for an antenna length of 400 microns. (c) Comparison between measured (blue curve) and simulated (dashed black curve) conversion efficiency.

In conclusion, we demonstrated a wireless electro-optic phase modulator based on TFLN photonic integrated circuit. Engineering the dispersion and antenna parameters allowed efficient phase modulation of wireless THz signals across the 80-400 GHz range. This work complements studies of guided wave THz-speed modulators and sources [7-9].

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