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# Optical-THz Conversion with a Triply-Resonant Thin-Film Lithium Niobate Photonic Molecule

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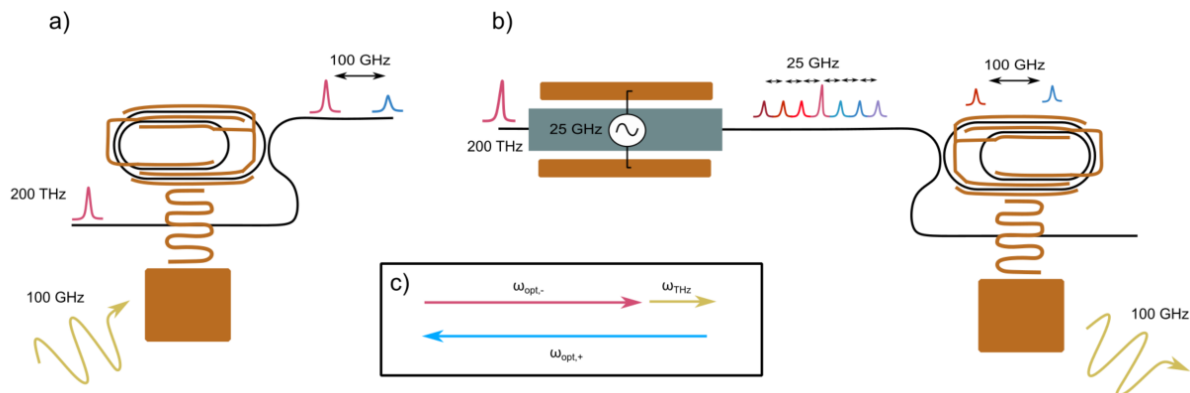
**Abstract:** We propose an optical-terahertz link using a triply-resonant photonic molecule and discuss its applications for terahertz signal detection and synthesis using traditional RF and optical techniques. Our design is a low-cost alternative to THz frequency generation via microwave drives and can be operated in both continuous-wave and pulsed regimes. © 2024 The Author(s)

## 1. Introduction

Leveraging the terahertz (THz) frequency range (.1-10 THz) is critical to meeting the high data traffic demands in modern communication infrastructure. While the past several decades has seen enormous development in THz communications technology, scaling these systems to realize an integrated, efficient THz communication system capable of broadband, reconfigurable operation remains an outstanding challenge [1]. Amongst various platforms, thin-film lithium niobate (TFLN) has emerged as a promising candidate to addressing these challenges thanks to its strong Pockels electro-optic coefficient ( $\sim 30$  pm/V), wide transparency window, and low propagation loss [2].

In this work, we propose a TFLN platform with a bidirectional, coherent link between sub-THz radiation and the telecommunication optical signals via three-wave mixing mediated by the Pockels effect (Fig. 1). We create a sub-THz frequency photonic molecule [3] by strongly evanescently coupling two optical resonators such that the eigenmodes are split by  $>100$  GHz. This can then be coupled to a THz resonator composed of a capacitive load inductively shunted to a THz waveguide or antennae, resulting in a triply-resonant three-wave mixing process. In general, the device can be operated as both a detector and synthesizer.

In the detection regime, an incident, resonant, THz wave coupled into the converter mixes with the resonant optical pump and scatters into the optical signal mode detuned from the pump by the THz frequency. The properties of the incident field can be extracted by analyzing the up-converted optical signal (Fig. 1a). In the synthesis regime, an optical pump and idler detuned by the converter frequency and resonant with the eigenmodes of the coupled optical resonator generate a coherent beatnote that is collected by the THz resonator and transmitted along the THz waveguide (Fig. 1b). Here, the device can also act as a filter to provide a low-cost alternative to THz frequency generation via microwave drives, which is typically achieved by beating two optical tones together on a photomixer [4]. Energy matching conditions (Fig. 1c) can be satisfied by thermally tuning the optical resonators or mechanically tuning the THz resonator.



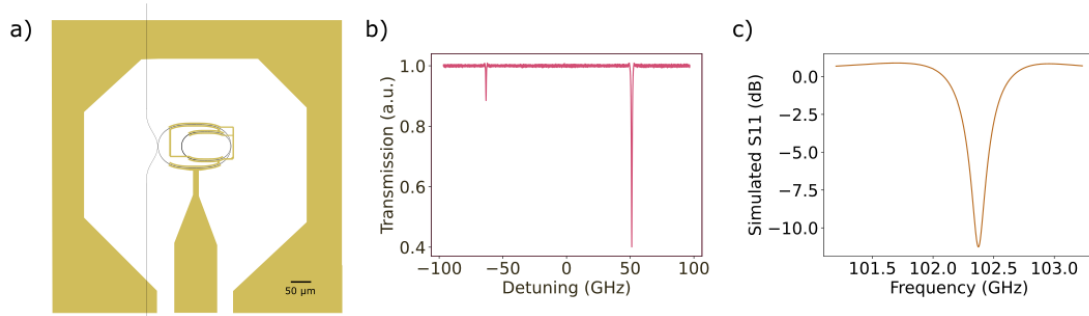
a) Scheme for THz-to-optical conversion, where a 100 GHz antenna coupled to a photonic molecule split by 100 GHz is upconverted to an optical signal via sum-frequency generation. b) Optical-to-THz conversion regime, where two optical tones detuned by 100 GHz interact to synthesize a 100 GHz wave via difference frequency generation. The radiation is collected in the THz resonator and emitted via a waveguide. The optical pump and idler fields can be generated from an electro-optic modulator driven at 25 GHz, with the photonic molecule filtering off two lines detuned by 100 GHz. c) Energy conservation for three-wave mixing.

## 2. THz-frequency photonic molecule

In our device, we use a nested paperclip structure to create our hybridized optical resonators in our photonic molecule. This allows us to maintain a small device footprint while gating the device primarily along the z-axis of the TFLN crystal. We simulate the device in COMSOL to estimate an electro-optic coupling rate of  $G_{EO} = n_{cav} \times 16$  kHz between the THz and optical regimes for a cavity-enhanced pump photon number  $n_{cav} = \frac{\kappa_e P_{pump}}{(\kappa/2)^2 \hbar \omega_{pump}}$ .

In our paperclip structure, two rings, one with an FSR of 220 GHz and the other with an FSR of 275 GHz, are tapered from 0.9  $\mu\text{m}$  in coupling regions to 3  $\mu\text{m}$  in straight sections of the waveguides to allow us to create low-loss optical resonators ( $Q_i \approx 1\text{M}$ ) split by  $2\mu = 111$  GHz. We note that, here, we are operating away from the degeneracy condition between the optical eigenmodes ( $2\mu_{ideal} \approx 50$  GHz), resulting in a 50% penalty to conversion efficiency between the THz and optical regimes. This can be overcome by placing the resonators closer together to increase the coupling rate or moving to a symmetric coupling structure to increase  $2\mu_{ideal}$ .

The hybridized optical resonators can be capacitively coupled to a gold THz resonator composed of the capacitive load inductively coupled to a THz waveguide (Fig. 1c), with a simulated quality factor of  $Q_{THz} = 12$  at 102.4 GHz. The splitting between the optical resonator modes can be thermally tuned to match the splitting to THz resonator frequency. From measured and simulated device performance, we estimate a bidirectional device efficiency exceeding 25% with 40 mW optical pump power.



a) Drawing of 100 GHz converter, where we inductively couple a shorted capacitive load to a 100 GHz waveguide to create a resonator (gold). The capacitive load is coupled to a TFLN photonic molecule (black). b) Optical transmission through the device, with measured mode splitting at 110 GHz. c) Simulated THz resonator transmission at 102.4 GHz.

## 3. Outlook

While the device discussed here is designed for operation around 100 GHz, the geometry of the optical resonators can be modified and realistically scaled to 200 GHz using a racetrack geometry and 500 GHz using ring geometries without significantly reducing optical quality factors. Integration of the device with microwave electro-optic modulators can provide a chip-scale solution to THz waveform synthesis with low-frequency microwave. The device can be operated in both the CW and pulsed regimes, and as a result can be combined with optical rectification techniques to provide a resonant enhancement to pulsed multi-cycle THz waveform synthesis [5,6]. Finally, integrating the device with on-chip THz photomixers [7] can enable the creation of low-loss, single pass, broadband frequency shifters [8], which can serve a fundamental role in scaling networks of quantum emitters and large-scale photonic computers.

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