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An on-chip dual-tone source for photonic-based terahertz transmitters

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Abstract We report a dual-tone source on thin-film lithium niobate for generating a tunable carrier frequency in the terahertz domain. The system achieves a stable carrier above 100 GHz, with sub-KHz linewidth and tunability over 5 GHz, offering a compact solution for integrated terahertz photonic systems.

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Introduction

To meet the growing demand for faster data transmission, high-speed and high-bandwidth transceivers are essential. Future wireless networks aiming for terabit-per-second data rates will need to operate at terahertz (THz) carrier frequencies, driving the need for compact, scalable, and cost-effective transceiver technologies [1].

It is equally important to recognize the strategic applications of such high-speed systems. Wireless THz communication is particularly valuable in scenarios requiring high data rates over short distances or in environments where atmospheric power attenuation is minimal. Key application domains include terabit-per-second wireless local area networks (Tera-WiFi), high-speed Internet of Things in data centers (Tera-IoT), integrated access and backhaul (Tera-IAB) wireless infrastructure, and ultra-broadband THz space communications (Tera-SpaceCom) [2].

Integrated photonics offers promising chip-scale platforms for THz applications [3]. Among the emerging platforms, thin-film lithium niobate (TFLN) stands out as an ideal wafer-scale solution for high-speed signal processing [4]. Its strong optical nonlinearity, broad transparency range, low propagation loss, high electro-optic coefficient, and wide modulation bandwidth make it highly suitable for THz applications. However, the absence of integrated light sources remains a major limitation. Recent efforts to integrate III-V components with TFLN [5] are a promising step toward realizing fully integrated THz photonic systems. In this work, we demonstrate an on-chip dual-tone source on the TFLN platform using a single laser, offering improved stability and reduced cost compared to dual-laser configurations.

Motivation and Prior Work

A key element in photonic THz transmitters is the dual-wavelength source [6], which generates two optical tones separated by a frequency fc. These tones beat together via photomixing to produce a THz carrier.

During the past decade, several chip-scale and integrated versions of such dual-tone sources have been developed on various platforms. The most straightforward technique for generating the dual-tone is to combine two free-running lasers, e.g., two DFB lasers [7,8,9,10,11], one DFB and one distributed Bragg reflector (DBR) laser [12, 13], or two DBR lasers [14,15]. Although this technique offers a compact device with a broad tuning range, it suffers from instability of the beat note and long term frequency drift. This instability stems from the fact that the two lasers have uncorrelated drifts. A locking technique, such as optical injection locking via an optical frequency comb, increases the stability and significantly reduces the beat note linewidth [7,8]; However, realizing an on-chip locking scheme is complicated and has not been demonstrated yet. Another method is to employ a dual-mode laser with multisection gratings [16,17,18]. In this way, although the generated beat note is stable, the difference between the modes cannot be largely tuned as both modes are mutually controlled via one laser. An ideal on-chip integrated photonics-based dual-wavelength source and eventually a transmitter must have the following criteria. In addition to low-optical loss, it has to host variety of devices such as lasers, detectors, and fast switches. The state-of-the-art dual wavelength sources are either monolithic devices on indium phosphide (InP) [7,8,10,11,12] or integrated III-V material-based devices on silicon (Si)-based platforms [9,16,17]. However, none of the these platforms can fulfil all the aforementioned criteria for an ideal system. Compared to other platforms, InP suffers a relatively high loss: insertion, propagation, and two photon absorption loss. The Si-based platforms cannot host high-speed and high-power optical components. Therefore, the community is addressing the needs by introducing other platforms and picking the best components from each platform and integrating them through hybrid/heterogeneous integration techniques and we propose it on TFLN which has an exceptional electro-optic and nonlinear-optic properties (electro-optic coefficient r_{33}~31 pm/V), as well as its wide transparency window (from 350 nm to 5 µm), and relatively high refractive index (~ 2.2 at 1550 nm).

The operation principle

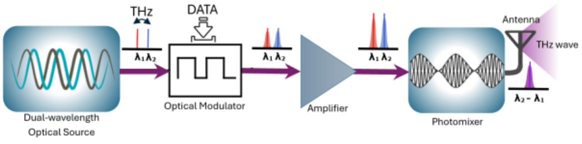

Fig. 2: Schematic diagram of a photonics-based THz transmitter

In a THz transmitter (Fig. 1), an optical signal with a sinusoidal envelope is generated using two light waves at two different wavelengths (λ_1 and λ_2). The wavelength difference ($\delta\lambda=\lambda_2-\lambda_1$) lies within the THz range of the spectrum. Then, the data is modulated using one/several optical modulators in any preferred techniques, including on-off keying (OOK), amplitude-shift keying (ASK), quadrature amplitude modulation (QAM), binary and quadrature phase-shift keying (BPSK and QPSK). The modulated signal is amplified (with gain G) and injected into a photodiode. Through photomixing, the photodiode generates a wave at the frequency of $f_c = \frac{c\delta\lambda}{\lambda_1\lambda_2}$, where c is the speed of light. Finally, the generated wave is radiated to the free-space using an antenna or is guided on-chip via a THz waveguide.

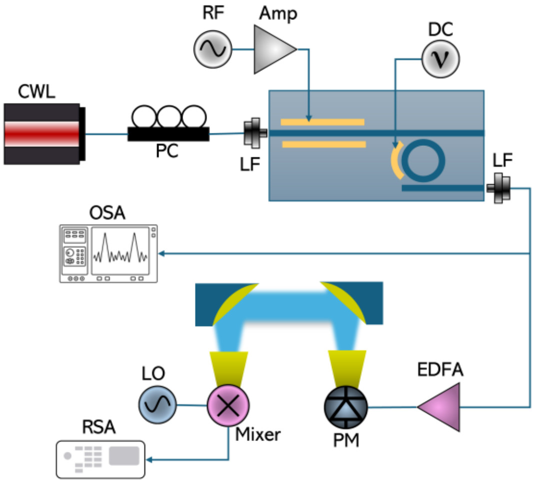

Fig. 3: Measurement Setup; CWL: Continuous Wave Laser, PC: Polarization Controller, LF: Lensed Fiber, EDFA: Erbium Doped Fiber Amplifier, Amp: Amplifier, PM: Photomixer, LO: Local Oscillator, OSA: Optical Spectrum Analyzer, RSA: Real-time Spectrum Analyzer

Results

Our dual-tone source comprises a phase modulator and a ring filter, both fabricated on commercial 600 nm X-cut TFLN on insulator wafers. (see [19] for fabrication details). A continuous-wave laser at 1550 nm is edge-coupled to the chip using lensed fibers. The generated dual-tone signal is amplified and sent to a commercial photomixer to produce a sub-terahertz carrier signal, which is collected via a horn antenna, downconverted, and analyzed using a real-time spectrum analyzer.

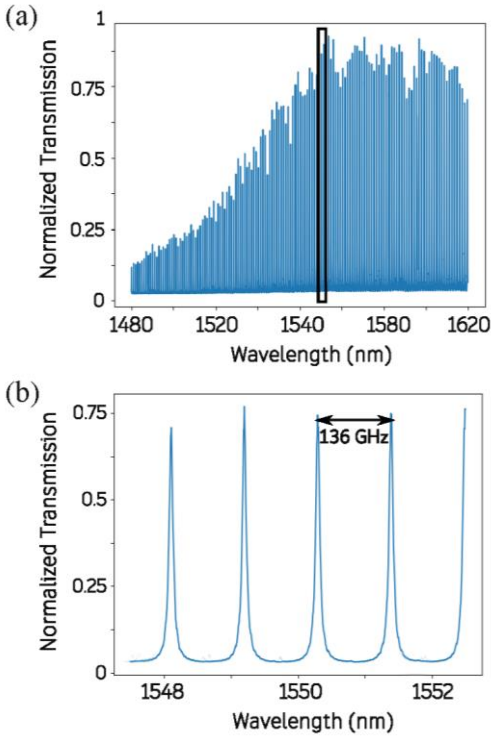

Fig. 1: (a) The transmission spectrum of the ring filter at the drop port. Panel (b) shows a magnified spectrum of panel (a) at 1550nm.

The characterization setup (Fig. 2) compares carrier generation from our chip against two free-running lasers. To generate the tones, a phase modulator driven at half the ring filter's free spectral range (FSR, 68 GHz) is used, followed by filtering with the ring resonator (extinction ratio: 20 dB) (Fig. 3).

The signal, filtered at the drop port (Fig. 4a), is amplified before photomixing. Our chip-based source generates a stable carrier at fc = 136 GHz with sub-kHz linewidth, while the dual-laser signal drifts by ~20 MHz. With pre-amplification, the detected signal shows a dynamic range of 32 dB (after 10 dB pre amplification) and 44 dB (after 10 dB pre amplification) as shown in Fig. 4b. The carrier frequency is tunable over more than 5 GHz (~4% of carrier frequency), determined by the modulation frequency and the loaded Q of the ring.

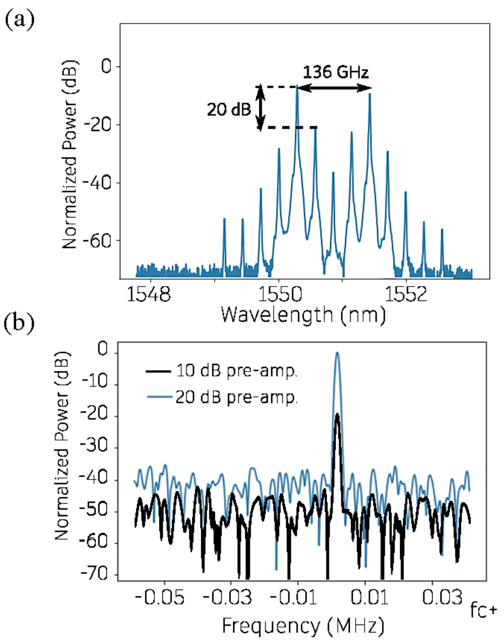

Fig. 4: (a) The signal collected with the lensed fiber before amplifier on optical spectrum analyzer,(b) Generated carrier frequency (fc = 136 GHz) on real-time spectrum analyzer.

Conclusions

Here, we demonstrate a compact, stable, and tunable dual-tone light source on the TFLN platform for generating a terahertz carrier frequency. Compared to systems using two free-running lasers, this approach offers notable advantages in stability and cost-efficiency.

Integrating this dual-tone source with on-chip photomixing [20] on the same platform paves the way toward a fully monolithic terahertz transmitter on TFLN.

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