Note on Ultrafast Tunable Lasers on Lithium Niobate

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Introduction

Lithium niobate is a material commonly used in high-speed modulators. The refractive index of this material changes linearly with an external electric field, an effect known as the linear electro-optic (EO) effect or the Pockels effect. The linear EO effect in lithium niobate is attributed to the broken inversion symmetry of its crystal structure [1]. The phase of light propagating in a lithium niobate waveguide can be tuned by applying an electric field, forming an EO phase modulator. By embedding this EO phase shifter into one arm of a Mach-Zehnder interferometer, an EO intensity modulator can be made.

In 2017, Zhang et al. demonstrated low-loss waveguides with strong optical confinement on monolithic integrated lithium niobate platform [2]. Their work is based on the thin-film lithium niobate (TFLN) on insulator platform. In contrast to conventional bulky lithium niobate modulators, where waveguides are formed through diffusive ion doping, this work uses standard nanofabrication processes (lithography and etching) to pattern the TFLN, producing compact waveguides with strong optical confinement, meanwhile sustaining low waveguide loss. This breakthrough enables the construction of integrated lithium niobate modulators with unprecedented performance in terms of modulation efficiency, bandwidth, and degree of integration [3], which are promising for next-generation optical communication technologies.

Recently, there has been a growing interest in transferring the excellent modulation performance of TFLN modulators to the fast tunability of integrated lasers. Specifically, laser external cavities fabricated on TFLN can provide narrow-band, electro-optically tunable reflection, enabling the development of ultrafast tunable lasers. These lasers are relevant to a range of applications, including high-speed optical communication and LiDAR. In this note, we introduce recent progress in ultrafast tunable lasers on lithium niobate and discuss the design principles of these lasers.

Typical Laser Architectures

Ultrafast tunable integrated lasers can be classified into self-injection-locked lasers and external-distributed Bragg reflector (E-DBR) lasers. A self-injection-locked laser comprises a distributed feedback (DFB) laser and a high-Q TFLN resonator. When the DFB laser is tuned so that its wavelength aligns with a resonance of the TFLN resonator, the resonator functions as a reflective filter and narrows the DFB laser linewidth. In this locking regime, the laser wavelength is locked to a resonant wavelength of the resonator, and laser wavelength tuning can be achieved simply by tuning the resonator. Using this method, an ultra-narrow linewidth of 56 Hz has been demonstrated on the TFLN platform [4]. While enabling very low-noise lasers, a major limitation of self-injection locking lies in the small chirp bandwidth. For instance, Snigirev et al. built an ultrafast tunable laser by locking a DFB laser to a hybrid lithium niobate/silicon nitride resonator in 2023 [5]; the chirp bandwidth of this laser is only 600 MHz. In the context of LiDAR applications, this chirp bandwidth translates to a low range resolution of 25 cm, which is insufficient for most practical uses. Additionally, self-injection locking is demanding in terms of operating conditions, such as injection current and ambient temperature, rendering these lasers sensitive to environmental fluctuations.

An E-DBR laser consists of a reflective semiconductor optical amplifier (RSOA) and a Bragg grating. E-DBR lasers can achieve narrow linewidths over a wide range of temperatures and currents, making them robust against environmental fluctuations and turnkey operable. To achieve narrow linewidth, the Bragg grating should have a low kappa (coupling coefficient between counter-propagating modes) for a narrow reflection bandwidth. Meanwhile, the grating should maintain sufficient peak reflectivity to ensure a low lasing threshold. Combining these two requirements, we find that narrow-linewidth DBR lasers must have a long, low-kappa

Bragg grating, which is unfortunately tricky to implement on the TFLN platform. This is due to variations in TFLN thickness for commercial TFLN on insulator wafers that degrade the uniformity and periodicity of long gratings, introducing undesired sideband reflections [6]. Given this technical challenge, the length of Bragg gratings on TFLN is typically limited to several millimeters, corresponding to a laser Lorentzian linewidth at the kHz or hundreds-of-Hz level [7].

A turnkey-operable, ultra-narrow-linewidth, widely and ultrafast tunable laser is highly relevant for high-precision LiDAR. However, as discussed above, the development of such a laser is constrained by architectural and material limitations and has not yet been reported on the TFLN platform. This gap indicates a potential research opportunity, and filling this gap deserves further investigation.

Design Principles

Narrow linewidth

To realize a narrow-linewidth, ultrafast tunable laser on TFLN, careful consideration should be given to waveguide loss, thermal noise, and gain chip properties. Among these factors, waveguide loss is directly linked to the reflection bandwidth of the external cavity and, consequently, to the laser linewidth. Below are a few suggestions for minimizing waveguide loss to achieve narrow-linewidth operation. First, the TFLN external cavity should employ a relatively wide waveguide, which may lead to multiple transverse modes, in order to reduce mode overlap with the sidewalls and minimize loss due to sidewall scattering. Second, the waveguide bending radius should be optimized to balance compactness and bending loss. Third, the metal electrodes should be positioned optimally to balance absorption loss and modulation efficiency (i.e., resonant wavelength shift per applied voltage).

The thermal noise in a TFLN external cavity is dominated by thermal-charge-carrier-refractive (TCCR) noise, as demonstrated in [4]. TCCR noise features an $f^{-1.2}$ scaling law (f refers to the frequency offset from the carrier frequency) and is fundamentally different from the well-known thermo-refractive noise. The TCCR noise in the TFLN external cavity sets a lower bound for the noise level of the hybrid integrated laser. The physical dimensions of the external cavity should be chosen so that the TCCR noise does not constitute a constraint for attaining the designed laser linewidth.

Additionally, the edge coupler of the TFLN external cavity should be properly designed to achieve high butt-coupling efficiency to the RSOA. The RSOA output facet should be anti-reflection (AR) coated to minimize undesired reflections from the facet, which degrade laser operational stability and may lead to multi-mode lasing. Moreover, the RSOA should have low amplifier spontaneous emission (ASE) power, as ASE acts as a noise source in the laser. Commercial C-band RSOA chips are available from Thorlabs and PHOTONX; among these, the RSOA from Thorlabs has lower ASE power and may be more suitable for building narrow-linewidth lasers.

Mode-hop-free tunability

During wavelength tuning, a TFLN-based ultrafast tunable laser may undergo abrupt changes in wavelength and power, known as mode hops. Mode hops result in wavelength ranges where the laser cannot operate, degrade power stability, and are undesirable in many applications. Mode hops occur due to spectral mismatch between the longitudinal mode and external cavity reflection, which happens when only one of them is tuned. One way to achieve mode-hop-free tuning is to synchronously tune both the longitudinal mode and the external cavity reflection. This can be accomplished, for example, by incorporating two phase shifters, one placed on the reflector and the other on the bus waveguide. If the voltages applied to these phase shifters maintain the correct proportionality, the laser wavelength can be tuned without mode hops.

Ultrafast tunability

The tuning signal is applied to the TFLN external cavity via direct contact of a probe with the device. To demonstrate a modulation bandwidth beyond 1 MHz while maintaining high modulation linearity, an RF probe must be used to avoid high-frequency signal distortion. The metal electrode on the device should be designed to be compatible with RF probe contact, such as using the ground-signal-ground (GSG) electrode configuration common in lithium niobate modulators. Moreover, the arbitrary waveform generator (AWG) and the RF amplifier must have sufficiently high bandwidth to enable the generation and amplification of high-frequency tuning signals.

Fabrication availability

Certain types of TFLN external cavities, such as the E-DBR architecture, involve sub-wavelength structures. These nanostructures are demanding on the fabrication process and require high-resolution lithography techniques. One approach to alleviate fabrication difficulties is to adopt higher-order gratings, which feature a period of $N\lambda_B/2n_{\text{eff}}$, where N is the Bragg order, λ_B is the center wavelength of reflection, and n_{eff} is the effective index of the waveguide. Since higher-order gratings ($N > 1$) have a relatively large period, fabrication is relatively simpler.

Reference

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