Ultrabroadband mid-infrared generation in
dispersion-engineered thin-film lithium niobate

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Abstract: We demonstrate efficient mid-infrared difference-frequency generation in
dispersion-engineered thin-film lithium niobate ridge waveguides on sapphire. These uni-
formly poled devices achieve phase-matching bandwidths in excess of a micron, and rapid
phase-matching peak tuning with temperature. © 2022 The Author(s)
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Thin-film lithium niobate (TFLN) is a rapidly emerging platform for linear and nonlinear nanophotonics [1]. While the vast majority of devices in this platform have been limited to visible and near-infrared wavelengths because of absorption past 2.5 μm in the commonly used silica undercladding, we recently demonstrated highly efficient mid-infrared generation in a TFLN-on-sapphire platform [2]. The tightly confining geometries of these nanophotonic waveguides also facilitate dispersion engineering, which recently has been used for broadband second-harmonic generation, supercontinuum generation, and broadband parametric amplification in TFLN [3,4]. In this work, we use the difference-frequency generation (DFG) process of a fixed 1.064-μm pump and a tunable telecom-band signal to demonstrate mid-infrared generation with more than a micron bandwidth in a single uniformly poled TFLN device with high normalized efficiency.

We obtain a MgO-doped X-cut TFLN wafer from a commercial vendor (NGK, Inc.). We periodically pole a TFLN chip of film thickness 940 nm using surface electrodes with a uniform periodicity of ~8 μm for quasi-phase-matching (QPM). Ridge waveguides with a nominal etch depth of 650 nm and top width of 3670 nm are then fabricated in the poled region using electron-beam lithography and argon-ion milling. The etch depth is estimated to be around 670 nm post fabrication. The chip facets are prepared for end-fire coupling by laser stealth dicing [3].

The nominal waveguide geometry is chosen based on group-velocity matching (GVM) between the signal and difference frequency (DF) waves (Fig. 1a) which facilitates broadband phase-matching. This geometry also allows for broadband transfer functions resulting from the turning point in the phase mismatch, and hence in the required poling period for QPM, at ~3400 nm (Fig. 1b).

The devices are characterized using the output of a tunable continuous-wave optical parametric oscillator (OPO; Toptica TOPO) which generates ~1 W of tunable near-infrared light in the range of 1.48–2.0 μm (OPO signal) from a pump at 1.064 μm. Both pump and signal from the OPO are simultaneously focused onto the input facet of a waveguide via a dichroic mirror and a reflective objective (Thorlabs LMM-40X-P01). The generated mid-infrared light is collected onto an amplified lead selenide photodetector. The signal wavelength is scanned to map out a device’s transfer function.

As shown in Fig. 1c, phase-matched DFG is observed over a wide mid-IR bandwidth, spanning from 2.9 μm to beyond 3.8 μm. The simulated transfer functions show reasonable agreement with the measurements after taking into account in the simulation the loss at the short wavelength end of the DF spectrum due to adsorbed water [2]. The poling period of this device is shown as a dashed line in Fig. 1b.

Figure 1d shows the measured transfer function from a device with a poling period 20 nm larger than indicated in Fig. 1b, that does not have the poling period non-criticality of the previous device, and therefore has a narrower transfer function compared to Fig. 1c, but nonetheless shows phasematching across hundreds of nanometers in the mid-IR. Fig. 1d also shows the transfer functions for the same device at three different temperatures, indicating rapid tuning of the phasematching with temperature, with a value greater than 10 nm per degree celcius.

Preliminary efficiency measurements indicate normalized DFG efficiencies of approximately 250%/W/cm² at phase-matching peak in these devices.

In conclusion, we have designed, fabricated, and characterized dispersion-engineered TFLN-on-sapphire devices that generate mid-IR light over bandwidth of hundreds of nanometers to over a micron via a difference-frequency process. These results show that TFLN-on-sapphire is a promising platform for ultrabroadband integrated nanophotonics in the mid-infrared, which will be applicable to a variety of devices such as broadly tunable sources and frequency combs based on near-IR pumps.
Fig. 1. (a) Simulated GVM between the input signal and the generated DF plotted as a function of TFLN film thickness and waveguide top width, with fixed etch depth. (b) Simulated variation of poling period (solid line) with respect to generated DF wavelength at 75 C for a fixed waveguide geometry: film thickness 940 nm, etch depth 670 nm and top width 3670 nm. Dashed line indicates poling period of the device measured in Fig. 1c. (c) Measured (dotted) and simulated (dashed) DFG transfer function at 75 C, plotted with respect to the generated DF wavelength for a fixed input pump at 1.064 μm and the corresponding signal input. (d) Measured DFG transfer function at three different temperatures for a waveguide, plotted with respect to the generated DF wavelength.

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