Highly Efficient Terahertz Generation via a Continuously Phase Matched Difference Frequency Generation in a Nested Waveguide Structure

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Abstract: We demonstrate continuously phase matched THz difference frequency generation (DFG) in a $LiNbO_3$ nested waveguide structure with a power-normalized conversion efficiency of 1.3 x 10^{-7} W^{-1}, 23 times more efficient than the best previously reported results [1].

I. INTRODUCTION AND BACKGROUND

Waveguides can enhance the efficiency of $\chi^{(2)}$ nonlinear optical processes, including difference frequency generation (DFG) of far-infrared (THz) light ($\omega_{THz}=\omega_{p1}-\omega_{p2}$), by providing well-confined collinear propagation without diffraction and with good pumps/product optical overlap. Meeting the phase matching condition ($\Delta\beta=\beta_{p1}-\beta_{p2}-\beta_{THz}=0$) in a simple cladding-core-cladding waveguide has typically required using pump and product guided modes of mixed order (modal dispersion) [2,3], compromising the confinement and overlap of the optical fields. We demonstrate that, with the proper choice of materials and dimensions, we can fabricate a pair of single mode 2-D (channel) waveguides, one for the two pumps nested inside a second one for the THz product, and achieve continuous phase matching with good optical confinement of the pumps and low THz mode propagation loss. This structure takes advantage of the large wavelength difference – and therefore a significant dimensional difference – between near-IR pumps and a THz product to provide nearly independent control of their single transverse mode properties.

II. RESULTS

The $LiNbO_3$-based structure is shown in Fig.1. The pump waveguide consists of a standard Ti-diffused channel waveguide [4], single mode at 1.5 μm, in a 14 μm $LiNbO_3$ c-oriented film. The single mode THz waveguide core is the whole of the $LiNbO_3$ film; the cladding layers are the quartz substrate and a high density polyethylene (HDPE) ridge, which also provides lateral confinement. Because of the strong confinement properties of the Ti diffused waveguide, the pump mode properties are essentially unaffected by the choice of THz waveguide parameters (i.e., the $LiNbO_3$ film thickness, for dimensions ~ 10 μm or greater, and the choice of outer cladding materials).

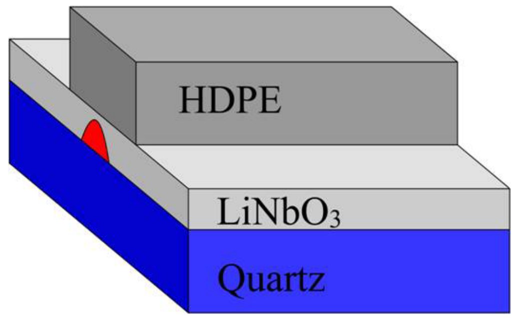

Fig. 1. Diagram of the $LiNbO_3$ nested waveguide structure. The two pumps are confined in a Ti:$LiNbO_3$ channel waveguide. The THz waveguide is formed by the $LiNbO_3$ film, quartz, and polyethylene ridge. The c-axis of the $LiNbO_3$ film is oriented normal to the film plane.

The phase matching condition for guided wave THz DFG can be written $n_{eff,THz} \sim n_{eff,p1,p2}$ where n_{eff} is the mode effective index. The THz waveguide parameters are used to control $n_{eff,THz}$ (with little or no influence on $\eta_{eff,p1,p2}$) and, therefore, can be chosen to meet the phase matching condition. Because the refractive index of $LiNbO_3$ in the THz is large ($n_{bulk} \sim 5$), low refractive index cladding layers (HDPE and quartz) are necessary to produce a THz mode effective index that is approximately equal to that of the two pumps in the near-IR ($n_{eff,p1,p2} \sim 2$). The output power of the $LiNbO_3$ nested waveguide structure was calculated using the TM mode profiles from full 2-D beam propagation simulations, including THz loss (Fig. 2). We note that as a result of the weak mode confinement, the THz mode loss was calculated to be $2\alpha_3 = 2$ cm^{-1}, which is much less than bulk $LiNbO_3$ ($2\alpha_{bulk} \sim 32$ cm^{-1}). A maximum output power of 104 nW is predicted at 1.38 THz using 760 mW pumps and a device length of 11 mm (the values used in the experimental work) (Fig. 3). The calculation was performed with no scaling factors.

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Outputs from an electrically modulated distributed feedback laser (spectral width ~ 2 MHz) and a tunable external cavity laser diode (spectral width ~ 0.2 MHz) were fed into polarization rotators, combined in a fiber coupler, amplified by an EDFA, and launched into the Ti:$LiNbO_3$ pump waveguide. Individual pump powers and polarizations were monitored out of the EDFA and held to 760 mW and TM, respectively. Fig. 3 shows the measured THz output power (via a liquid He Si bolometer) from the $LiNbO_3$ nested waveguide structure of Fig.1 vs. frequency difference between the pumps. The data is referenced to a residual background level of 1.3 nW (with pumps on and the frequency difference far from phase matching) and re-scaled to account for losses absorption losses in the collection optics.

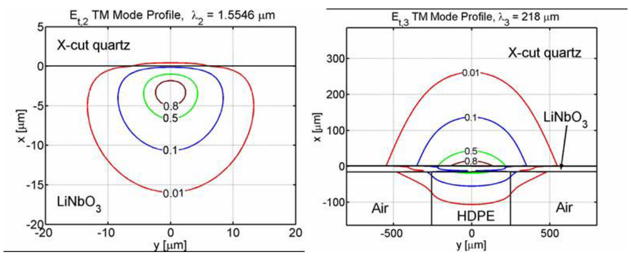

Fig. 2. TM electric field profiles in the nested Ti:$LiNbO_3$ waveguide at $\lambda_2 = 1.5546$ µm for (a) the pump modes, and (b) for a 1.38 THz (λ_3 = 218 µm) mode. The peak electric field amplitude is normalized to 1 in both plots. Both waveguides are single mode.

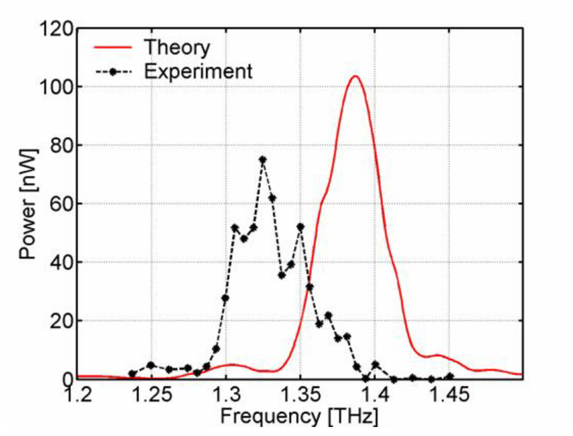

Fig. 3. Measured and calculated output power from the $LiNbO_3$ nested waveguide structure vs. THz frequency for 760 mW CW near-IR pumps.

A maximum output power of 75 nW occurred at 1.325 THz, with a FWHM of ~ 0.5 THz. Because THz output power scales as the product of the two pump powers, it is necessary to use a power-normalized conversion efficiency, $\eta_p = P_{THz}/P_{p1}P_{p2}$. which for our experiment was $\eta_p = 1.3 \times 10^{-7}\ W^{-1}$ – 23 times larger than that extracted from the best previously reported results [1]. The two absorption troughs located at 1.312 and 1.337 THz were observed in repeated experiments, and maybe due to the thin epoxy layer or fine absorption features in air.

The calculated DFG output power shown in Fig. 3 is in excellent agreement with experiment when shifted by –57 GHz. This discrepancy is likely due to a slightly higher THz effective index due to the 2 µm epoxy layer between the $LiNbO_3$ and quartz. We estimate that another two orders of magnitude in the normalized power conversion efficiency could be gained by replacing the absorptive $LiNbO_3$ with a lower loss nonlinear material. The nested waveguide configuration thus appears to be a powerful method to achieve much more efficient THz generation – in part because it allow us to take advantage of a broad range of material and structural combinations. Since the output THz power is proportional to the product of the two pump powers, the peak output power of the $LiNbO_3$ nested device can be dramatically increased by replacing the very modest CW pump powers used in this experiment with the high output powers available from pulsed fiber lasers.

III REFERENCES

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