Efficient terahertz generation schemes in thin-film lithium niobate platform

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Abstract: We propose two schemes for efficient continuous-wave terahertz generation based on lithium niobate on insulator platform via DFG. The efficiencies are as high as 2.1×10^{-2} W^{-1} at 3 THz and 1.2×10^{-3} W^{-1} at 300 GHz.

1. Introduction

The terahertz (THz) frequency ranging from 0.3 to 10 THz, is of particular interest for critical scientific and technological applications. In the past decades, many techniques for THz wave generation using electronic and optical methods have been proposed and demonstrated [1]. Among them, difference frequency generation (DFG) is a particularly interesting scheme for generating continuous-wave THz radiation and enjoys a quadratic scaling with frequency (efficiency ~ ω^2). Lithium niobate ($LiNbO_3$, LN) is of particular interest for THz-DFG due to its large $\chi^{(2)}$ nonlinear coefficient (390 pm/V in the THz region) [2]. Herein, we propose two integrated photonic schemes that can dramatically increase the DFG-THz generation efficiencies compared with their bulk counterparts. The theoretically predicted conversion efficiencies are as high as 2.1×10^{-2} W^{-1} at 3 THz and 1.2×10^{-3} W^{-1} at 300 GHz.

2. THz generation at 3 THz using a hybrid LNOI-silicon platform

Fig. 1(a) shows the schematic of the first scheme, intended for generation of high-frequency THz waves (~ 3 THz). Two optical laser signals in the telecom band are frequency mixed for the generation of 3-THz signal. The top thin-film LN waveguide provides low-loss optical confinement and $\chi^{(2)}$ nonlinearity for the DFG process. The bottom Si waveguide collects and continuously guides the generated THz waves such that the nonlinear interaction could coherently build up. An intermediate SiO_2 layer is used to prevent the optical mode from leakage into the Si substrate. Finally, the LN/SiO_2/Si stack sits on top of a quartz substrate. Fig. 1(b) shows the simulated THz (main panel) and optical (inset) mode profiles, both in transverse-electric (TE) polarization. The simulated THz loss of the Si waveguide is ~ 7 dB/cm at 3 THz, sufficient to support a total device length of > 1 cm without excessive THz loss. The multi-layer stack allows us to independently tune the effective indices of the optical and THz waves, such that the phase-matching condition ($\Delta k = k_{\mathrm{opt1}} - k_{\mathrm{opt2}} - k_{\mathrm{THz}} = 0$) could be fulfilled ($n_{\mathrm{THz}} = n_{\mathrm{g,opt}} = 2.27$). For a fixed waveguide parameter, the phase-matching bandwidth is ~ 25 GHz for a device length of 1 cm. For a 1-cm device, the optimal conversion efficiency is 1.3×10^{-4} W^{-1} [Fig. 1(c)]. The maximal efficiencies for 2-cm and 3-cm devices are 2.6×10^{-4} W^{-1} and 3.5×10^{-4} W^{-1} respectively. When the length is beyond 1-cm, the power scaling deviates from the quadratic dependence due to THz losses [inset of Fig. 2(b)]. These efficiencies are three orders of magnitude higher than current LN-based DFG devices at room temperature [3].

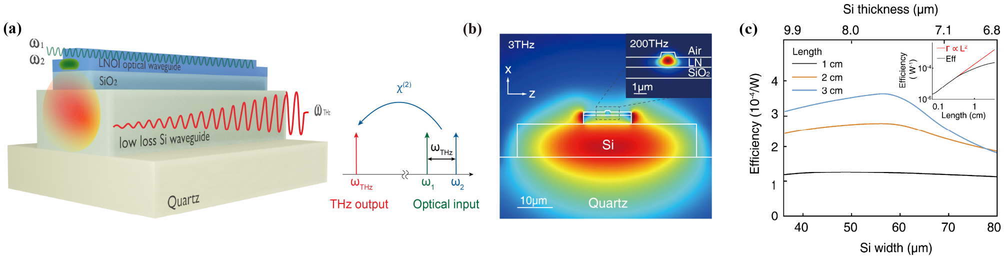

Fig. 1. (a) Schematic diagram of the proposed THz source. (b) Numerically simulated electric field distributions (E_z) of the THz mode at 3 THz (main panel) and the optical mode at 200 THz (inset), showing strong field confinement at both frequencies. (c) Conversion efficiency as a function of the Si waveguide dimension in cases of various device lengths.

3. Millimeter-wave generation at 300 GHz using a ground-signal-ground transmission line

Fig. 2(a) shows the schematic of the second scheme for millimeter-wave (MMW) generation at ~ 300 GHz using a ground-signal-ground (GSG) transmission line structure similar to that of an electro-optic modulator. Again, two optical laser signals are frequency mixed for the generation of 300-GHz signal. The output MMW can be straightforwardly extracted using a GSG MMW probe. High MMW generation efficiencies could be achieved by optimizing the electro-optic overlap, matching the velocities between light and microwave, and controlling the optical and microwave propagation losses, simultaneously. The simulated microwave (main panel) and optical (inset) mode profiles are shown in Fig. 2(b). The thin-film LNOI configuration allows for maximum field overlap and velocity matching between microwave and optics by designing the LN/SiO_2/Si-stack and the metal electrode dimensions. We design the waveguide width (1 μm), ridge height (300 nm) and metal gap (5 μm) to achieve the optimum electro-optic overlap and the signal electrode width (20 μm) and the substrate SiO_2 thickness (2 μm) to achieve group velocity matching between microwave and optics. When taking into account the absorption of the transmission line (2 dB/mm at 300 GHz), the conversion efficiency is dependent on the total device length, since a longer device experiences a higher microwave loss [Fig. 2(c)]. A 1 cm long device could yield an overall conversion efficiency of 3.0×10^{-6} W^{-1} in continuous-wave operation.

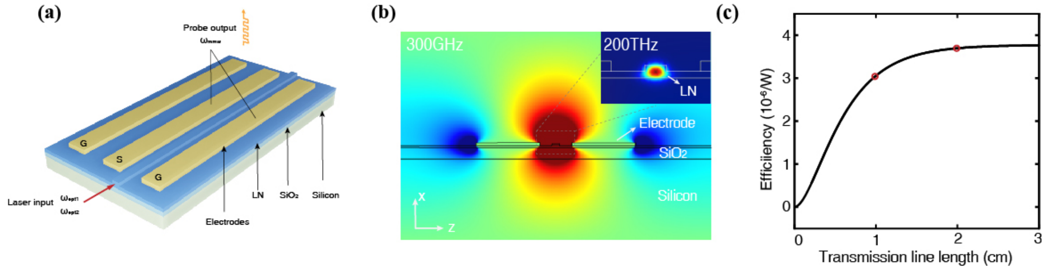

Fig. 2. (a) Schematic of the proposed MMW source. (b) Numerically simulated electric field distributions (E_z) of the MMW mode at 300 GHz (main panel, showing one half of the GSG structure) and the optical mode at 200 THz (inset). (c) Conversion efficiency as a function of the length of the transmission line.

4. Efficiency improvement

The THz/MMW generation efficiencies can be further improved by orders of magnitude using a racetrack optical resonator. Instead of running the optical pumps through the device only once, we take advantage of the ultra-low-loss nature of the LNOI platform to further increase the effective pump powers using optical cavities. We assume a racetrack resonator with a bending radius of 80 μm and a straight-section length of 2 mm, which is critically coupled with a loaded Q factor of 1×10^{6} [4]. In this case, the effective pump power sees a 48-times amplification inside the resonator compared with the power in the bus waveguide. If both optical pumps are tuned into resonance, the system conversion efficiency is enhanced by a factor of ~2,280 from a 2-mm waveguide device. That is, from 9.3×10^{-6} W^{-1} to 2.1×10^{-2} W^{-1} at 3 THz for the hybrid LNOI-silicon platform, and from 5.2×10^{-7} W^{-1} to 1.2×10^{-3} W^{-1} at 300 GHz for the MMW transmission line configuration, representing two/three orders of magnitude increase from the non-resonant best-case scenario with a more compact footprint.

5. Conclusion

In conclusion, we have investigated two schemes of efficient continuous-wave THz/MMW sources based on LNOI platform. Using a racetrack resonator structure, we show the THz generation efficiency can be further increased to 2.1×10^{-2} W^{-1} (3 THz) and 1.2×10^{-3} W^{-1} (300 GHz), orders of magnitude higher than current DFG-based THz/microwave sources. The efficient THz/MMW sources could become key elements for future spectroscopy, imaging and communication systems.

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