Spatial mode selection in a terahertz Lithium Niobate waveguide using chirped and temporally delayed optical pulses

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Abstract: We present a method for selective terahertz mode generation in a periodically poled lithium niobate waveguide using chirped and delayed laser pulses (CADLP). Additionally, a thin-film lithium niobate-silicon hybrid waveguide sows potential for terahertz mode selection.

1. Introduction

Terahertz (THz) radiation has attracted considerable interest from both the scientific and industrial communities. Multimode propagation in THz waveguides introduces an additional degree of freedom for achieving advanced functionalities. Numerous THz generation techniques have been explored, particularly optical approaches that employ nonlinear optical processes in nonlinear materials. Among them, the chirped and delayed laser pulse (CADLP) technique stand out for its ability to produce narrowband THz radiation with high efficiency and tunability [1]. Lithium niobate (LN) is a promising nonlinear material for THz generation due to its large nonlinear optical susceptibility. However, the generated THz wave cannot be coherently built up naturally in LN due to the velocity mismatch between the optical light and the THz wave. Several techniques have been explored to overcome this limitation of [2-4], such as quasi-phase-matching by using periodically poled lithium niobate (PPLN) and modal phase-matching by engineering the dispersion properties of the waveguide. Herein, we numerically validate an efficient method for selectively generating specific guided modes in multimode waveguides using the CADLP technique. An ultrashort pulse is temporally stretched into a long chirped pulse. A pair of chirped pulse are created and recombined interferometrically with a relative temporal delay, producing an intensity beating that typically lies in the THz range. In a multimode waveguide, each guided THz mode is characterized by its own dispersion relation. the phase-matching condition between the optical excitation and the THz wave is satisfied only for specific combinations of frequency and guided mode. By tuning the relative delay, we can select which guided mode is excited in the waveguide.

2. Results

We selected an initial optical pulse duration of τ_0 = 380 fs, which was subsequently stretched to τ = 100 ps. Figure 1(a) shows the schematic of a PPLN waveguide with a cross-section of 500×500 μm^2 pumped by a pair of chirped and delayed pulses with a relative delay time of ΔT. The phase-matching condition is not directly met in the waveguide with such a large cross-section. The wavevector mismatch between the optical field and THz modes can be compensated by $\Delta k = 2\pi/\Lambda$ in the PPLN waveguide with a poling period of Λ = 223 μm. Figure 1(b) shows the phase matching for the three modes in the PPLN waveguide. The quasi-phase-matching condition is met for the TE_{00}, TE_{10}, and TE_{20} modes at 488 GHz, 494 GHz, and 510 GHz respectively. The insets show the corresponding mode profiles. In our CADLP configuration, ΔT is set at 41.9 ps, 42.5 ps, or 43.9 ps to match the frequency at which the quasi-phase-matching condition is met for the TE_{00}, TE_{10}, or TE_{20} modes, respectively. We numerically calculated the conversion efficiency of these three THz modes for the selected relative delay time by employing coupled-wave equations [2]. Figure 1 (c) shows the conversion efficiency as a function of the waveguide's length for the ΔT = 41.9 ps. The conversion efficiency of the TE_{00} mode increases monotonically with waveguide length, reaching a saturation value of approximately 7×10^{-4} at around 1.5 cm. This saturation arises from THz absorption in the waveguide. Indeed, when the absorption coefficient is set to zero in the numerical simulations, the efficiency continues to increase monotonically with waveguide length. In contrast, the TE_{10} and TE_{20} modes exhibit an initial increase in efficiency at short propagation lengths followed by a rapid decrease for longer waveguides. This behavior is attributed to their phase-mismatched propagation, which leads to destructive interference and, consequently, a decrease in efficiency after the initial growth phase. As shown in Figure 1(d) and (e), when applying a relative delay of 42.5 ps or 43.9 ps, the TE_{10} and TE_{20} modes, respectively, are efficiently generated. In both cases, the conversion efficiency of the preferentially excited mode increases with waveguide length up to approximately 1.5 cm, while those of the other two modes remain at relative low values.

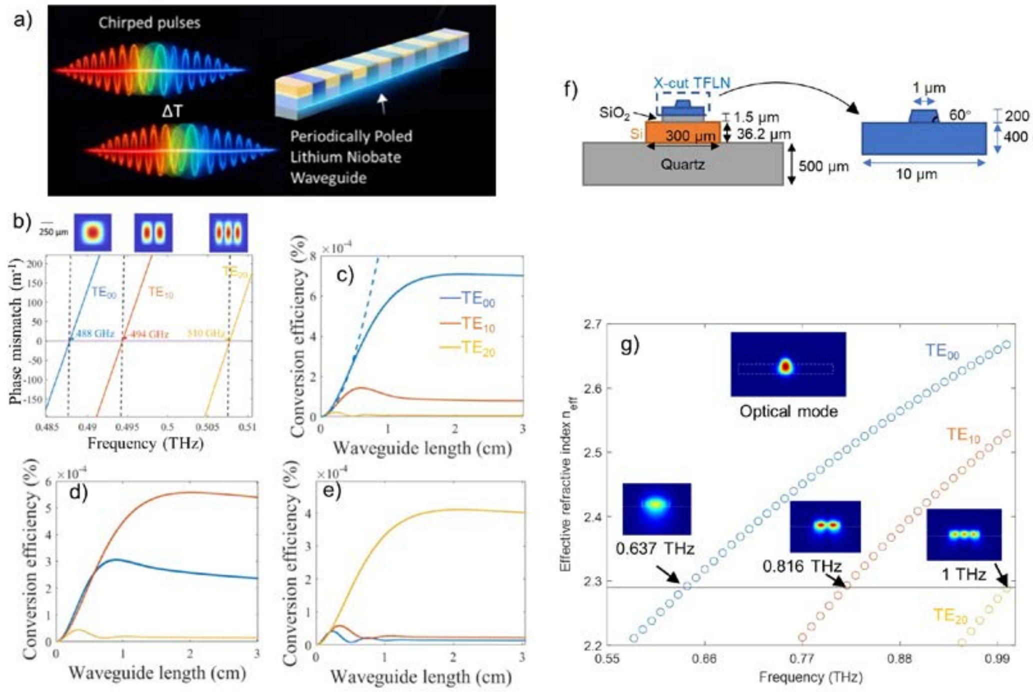

Fig. 1. (a) Schematic diagram of the spatial mode selection technique using CADLP in PPLN. (b) Phase matching for the three modes in a PPLN waveguide with a cross-section of 500×500 μm^2. (c)-(e) Efficiency as a function of the waveguide length for the TE_{00}, TE_{10} and TE_{20} modes for a ΔT = 41.9 ps, 42.5 ps, and 43.9 ps respectively. (f) Schematic diagram of the proposed thin film lithium niobite-silicon hybrid waveguide. (g) Simulated dispersion relation of the hybrid waveguide at THz frequency. The insets are the optical mode in LN and THz modes in silicon core.

We also numerically investigated a thin-film lithium niobate-silicon (TFLN-Si) hybrid multimode waveguide. Figure 1(f) shows the structure of the proposed waveguide. The TFLN layer is patterned into a ridge waveguide for guiding optical light. The THz wave can be generated in the TFLN waveguide and leaks into the surrounding material. The silicon waveguide is used to collect and guide the generated THz wave from the TFLN waveguide [4]. The velocity of the optical field in the TFLN waveguide and that of the THz field in the Si waveguide can be matched in an optimal structure with specific dimensions. As a result, the generated THz wave can be coherently built up and the conversion efficiency is expected to be enhanced through the modal phase-matching without the need of periodic poling process. In addition, the absorption is reduced owing to the THz wave propagating in the high resistivity silicon waveguide rather than in LN. Figure 1(g) shows the dispersion relation in the THz band. The top inset shows the optical mode in the TFLN ridge waveguide. The group index of the optical mode centered at 1030 nm is n_g = 2.99, as indicated by the solid black line. At the crossings of the solid black line with the dispersion relation curves (marked by circles), the modal phase-matching condition is met. The lower panel insets show the phase-matched THz mode profiles of the TE_{00}, TE_{10}, and TE_{20} modes at 0.637 THz, 0.816 THz, and 1 THz respectively. The modal phase-matching in this hybrid multimode waveguide suggests that it is possible to selectively generate THz mode by using the CADLP technique, similar to the previous PPLN scheme.

3. References

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