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Widely tunable dual-color waveguide-based optical parametric oscillator

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ABSTRACT: Exploiting four-wave mixing in two orthogonally polarized fundamental modes of Si_3N_4 waveguides and a tunable birefringence in the cavity, an optical parametric oscillator generates two independently tunable output frequencies from 0 to 62 THz difference.

1. Introduction

Tunable laser sources have many applications in metrology, spectroscopy, or microscopy [1]. Lasers can usually generate ultrashort pulses at a single center frequency, which is insufficient to drive multi-color experiments. By exploiting nonlinear gain, optical parametric oscillators (OPOs) offer an additional independently tunable output wavelength with respect to the pump laser's wavelength, rendering them ideal sources for multi-color experiments [1,2]. While dual-output OPOs have been explored in bulk crystals, e.g., by using two crystals for parametric oscillation [3,4], we present a waveguide-based OPO (WOPO) that exploits orthogonally polarized fundamental modes of a Si_3N_4 waveguide and a tunable birefringence to generate two independently tunable outputs.

2. Experimental Setup

The experimental setup comprised a polarization-maintaining (PM) cavity, shown in Fig. 1(a), that enabled independent oscillation of two waves in orthogonal polarizations by offering two independent cavities. The OPO exploited four-wave mixing (FWM) in rectangular Si_3N_4 waveguides ($W \times H \times L = 650\,\text{nm} \times 800\,\text{nm} \times 10\,\text{mm}$), offering FWM gain for its two orthogonally polarized fundamental TE and TM modes, see Fig. 1(b). Upon pumping with pump pulses at 1030 nm center wavelength and with 1 ps duration, signal and idler pulses were generated, of which the signal pulse was coupled into a PM fiber to seed the FWM process. Dispersive tuning was employed to tune the idler wavelength: Due to group velocity dispersion, the broadband signal pulse is chirped in the fiber, such that the temporal overlap of this chirped (seed) signal pulse with the next pump pulse determines the idler wavelength. A balanced Mach-Zehnder interferometer based on polarizing beam splitters was used to control the overall birefringence of the cavity by adjusting the lengths of the two cavities independently.

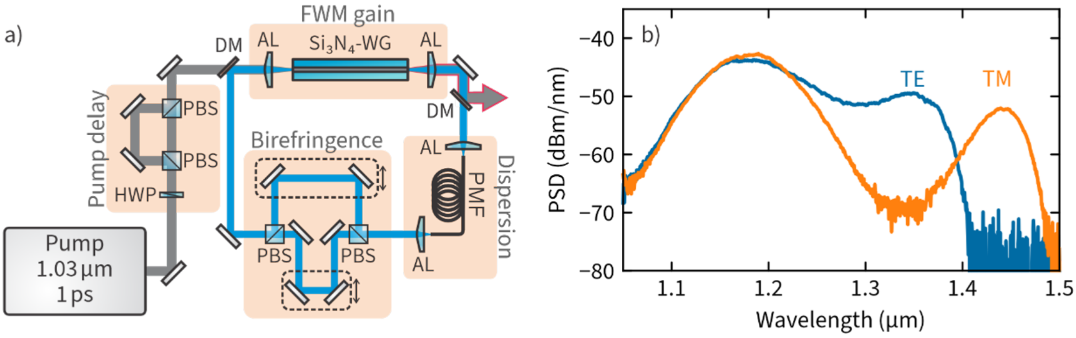

Fig. 1. a) Schematic experimental setup. HWP: half-wave plate, PBS: polarizing beam splitter, DM: dichroic mirror, AL: aspheric lens, PMF: polarization-maintaining fiber. b) Exemplary power spectral density (PSD) of spontaneous four-wave mixing in the Si_3N_4 waveguide at 0.75 nJ and 1.10 nJ for the TE and TM modes, respectively, compensating differing coupling efficiencies of the pump beam to the modes.

The pump energy coupled into each waveguide mode was adjusted with a half-wave plate behind the pump laser. Additionally, a delay was introduced for the TM-polarized pump beam to avoid intermodal FWM, appearing when the two pump pulses were simultaneously coupled into the waveguide. Such a delay (with inverted arms) could also be introduced at the output to temporally overlap the idler pulses of different wavelength in time.

3. Results

First, the WOPO was pumped with either TE or TM polarization and the cavity was blocked to ensure FWM gain was available in both modes, indicated by spontaneous FWM (see Fig. 1(b)). Then, the cavity was unblocked and the lowest threshold of each mode was observed at 0.475 nJ and 0.675 nJ external pump energy for TE and TM mode, respectively (see Fig. 2(a)). This pump energy difference can be explained by different coupling efficiencies of the pump beam to the modes, indicated by transmission of 40% and 17% for TE and TM mode, respectively. Nevertheless, the ratio of these thresholds matched the pump energy ratio observed to get equally strong spontaneous FWM (see Fig. 1(b)), indicating that at these pump energies, both modes exhibited the same FWM gain to overcome the cavity losses. Furthermore, the maximum output energies of the two modes were limited due to cascaded FWM, in case the frequency of cascaded FWM was located within the broadband FWM gain (compare Fig. 1(b)). In the future, to avoid strong cascaded FWM, a different waveguide geometry could be used that exhibits a narrow gain bandwidth for one mode, and a large gain bandwidth for the second mode.

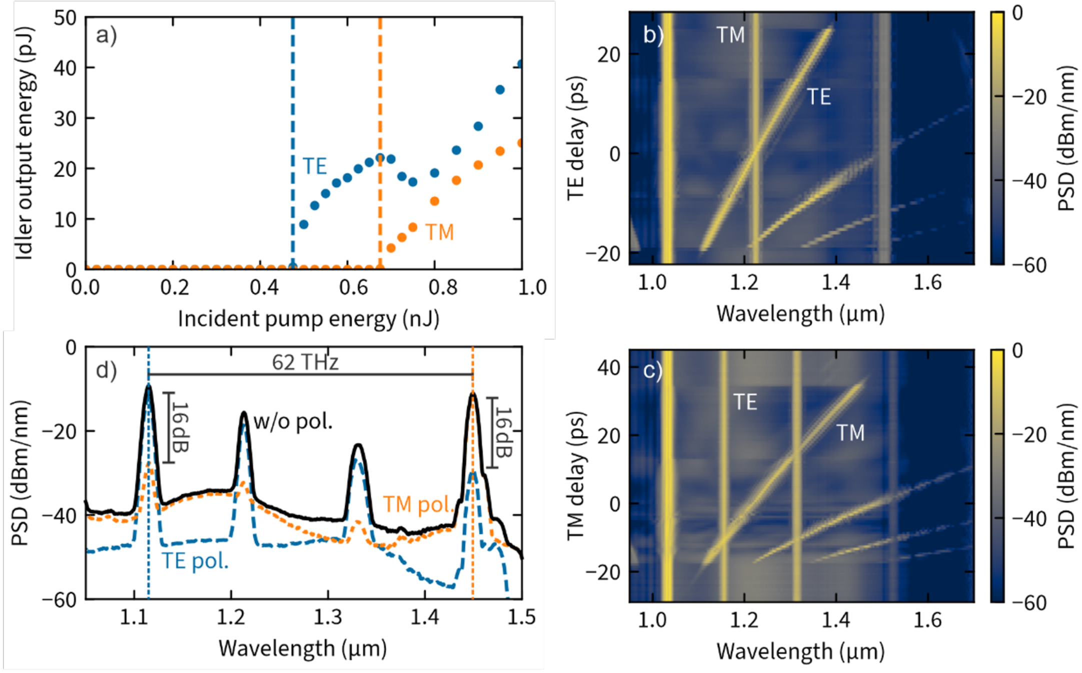

Fig. 2. a) Energy of TE and TM idler waves with oscillation thresholds marked with dashed lines. b) Power spectral density (PSD) of WOPO output showing tuning of TE idler wavelength with TM wavelength fixed to 1.22 µm at pump energies of 1.4 nJ and 1.0 nJ for TE and TM mode, respectively. c) Tuning of TM idler wavelength with TE wavelength fixed at 1.16 µm at pump energies of 0.68 nJ and 1.55 nJ for TE and TM mode, respectively. d) PSD of WOPO output without a polarizer (black), and with a polarizer transmitting TE (blue, dashed) or TM mode (orange, dotted). The annotated maximum idler wavelength separation of 62 THz was obtained at pump energies of 1.1 nJ and 1.4 nJ for TE and TM mode, respectively.

In order to show independent tunability of the idler wavelengths, both modes were pumped, such that the WOPO generated two outputs. First, the wavelength of the TM mode was fixed to an arbitrarily chosen 1.22 µm, and the wavelength of the TE mode was continuously tuned by 53 THz from 1.11 µm to 1.38 µm by adjusting the optical delay line in the TE-arm of the Mach-Zehnder interferometer (see Fig. 2(c)). Second, the wavelength of the TE mode was fixed to 1.16 µm and the TM idler was tuned over 61 THz from 1.12 µm to 1.44 µm (see Fig. 2(d)), showing that tuning one idler wavelength did not affect the other.

Combining the settings for smallest TE idler wavelength with largest TM idler wavelength, a maximum separation between the idler frequencies of 62 THz was obtained in experiment (see black line in Fig. 2(d)). Moreover, in order to prove that each of the two outputs was generated by the accordingly polarized copy of the pump pulse, a polarizer was put behind the WOPO output to transmit either the TE or the TM mode (dashed blue or dotted orange line in Fig. 2(a), respectively). The observed polarization extinction ratio was 16 dB, which matched the extinction ratio of the pump pulse polarizations behind the WOPO output, indicating polarization cross-talk at the inverse tapers of the waveguide facets.

4. Conclusion

To sum up, we presented a waveguide-based OPO with two independently tunable and orthogonally polarized output wavelengths. In the future, a balanced pump delay could be employed to investigate the effect of intermodal FWM on the OPO. And an optimized waveguide geometry should allow to reduce the appearance of cascaded FWM. Additionally, the two outputs could be applied, e.g., in dual-probe spectroscopy or microscopy with the two idler waves having a frequency difference from arbitrarily small to up to 62 THz.

5. References

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