Synchronously pumped optical parametric oscillator with a spatially dispersed beam

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Synchronously pumped optical parametric oscillator (SPOPO) is a conventional apparatus used for wavelength-tunable infrared light sources [1–3]. Periodically poled materials have been used in several SPOPO experiments because these materials provide several advantages such as high nonlinear coefficients and lack of spatial walk-off [4-6]. In addition, they have a significant advantage that various structures with different poling periods can be flexibly designed [7]. Furthermore, structures with chirped or fan-out poling periods have been developed [8-10].

Chen et al. proposed a method for an optical parametric amplifier (OPA) using a fan-out type poled device [11]. In this method, broadband phase matching was achieved by adjusting the fan-out poling period and the spatially dispersed beam. The frequency-domain OPA is a similar method that uses a spatially dispersed beam [12]. In this study, the demonstration of a broadband SPOPO is presented using a fan-out type poled device and a spatially dispersed beam [13].

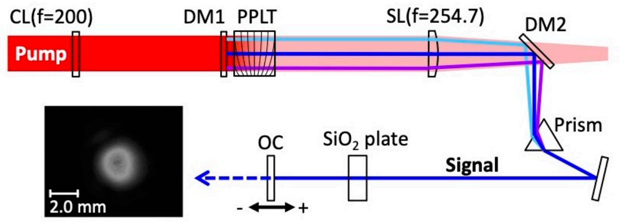

Fig. 1. Optical layout of the SPOPO. It consists of components such as spherical lens (SL), cylindrical lens (CL), periodically poled $LiTaO_3$ (PPLT), dichroic mirrors (DM1 and DM2) that reflect only the signal light, and an output coupler (OC) with a signal light transmittance of 50%. The inset depicts the output signal beam profile measured at a distance of 1.7 m from the OC.

An Yb-doped fiber laser was used as the pump source for the SPOPO. The laser had a repetition frequency of 43.3 MHz, central wavelength of 1038 nm, full-width at half-maximum (FWHM) pulse length of 390 fs, and a maximum pump power of 14 W. Fig. 1 shows the optical layout of SPOPO. This layout was similar to that used in a previous study [14]. MgO-doped periodically poled $LiTaO_3$ (MgO:PPLT) was used as the nonlinear material. The output coupler (OC) had a constant transmission rate of 50% in the frequency range of 1300 – 1700 nm. The cavity length was 3.46 m, which corresponded to the repetition frequency of the pump laser. Flat mirrors were used in the cavity for dichroic mirrors (DM1 and DM2) and the OC. Only one spherical lens was used in the cavity. The spherical lens was made of CaF_2 with a broadband anti-reflection (AR) coating and it had a focal length of 254.7 mm for a wavelength of 1580 nm.

An N-SF11 glass equilateral prism was installed in the cavity. Fig. 2 shows the details of the fan-out type MgO:PPLT and the spatially dispersed beam. The prism had an AR coating for the wavelength range of 1500 – 1700 nm when the S-polarization light was incident at an angle of 60.6°. The prism generated an angular dispersion of $\Delta\theta/\Delta\lambda$. The spatial displacement at the spherical lens was $\Delta X/\Delta\lambda = f\Delta\theta/\Delta\lambda = 9.3 \times 10^{-3}$ mm/nm, where f is the focal length. In Fig. 2, the three lines represent signal beam axes with different wavelengths. The beams were parallel between DM1 and the spherical lens, and coaxially overlapped between the prism and OC.

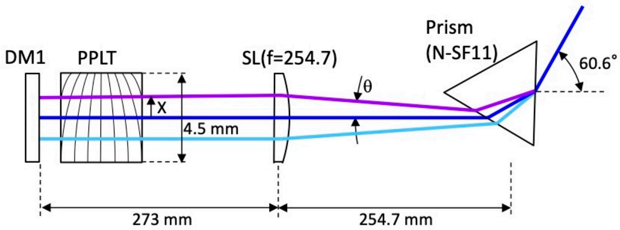

Fig. 2. Details of the fan-out type MgO:PPLT and the spatially dispersed beam.

The nonlinear crystal was 1 mol% MgO-doped stoichiometric PPLT (manufactured by OXIDE). The crystal had a broadband AR coating in the range of 1000 – 1700 nm and it had a length (Z-direction), height, and width (X-direction) of 10, 2, and 6 mm, respectively. The effective width was 4.5 mm, where the poling period had a nonlinear fan-out structure and it varied in the range of 28.6 – 32.4 μm. Fig. 3(a) shows the relationship between the position X in the MgO:PPLT and the poling period. The fan-out structure was designed to exhibit a linear relationship between horizontal position (X) and the signal wavelength, as shown in Fig. 3(b). The slope of the linear relation was $\Delta X/\Delta\lambda = 9.24 \times 10^{-3}$ mm/nm, which was equal to the value obtained by the prism dispersion.

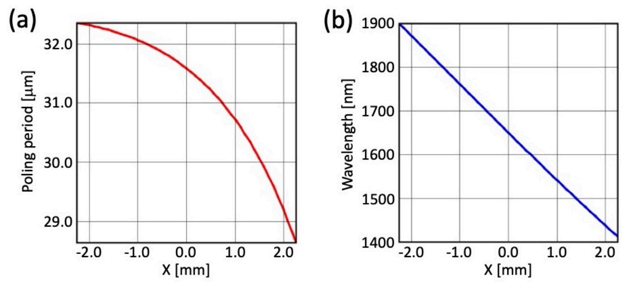

Fig. 3. (a) Poling period of MgO:PPLT as a function of the horizontal position (X). (b) Signal wavelength that satisfies the phase-matching condition as a function of X.

The spectral dispersion in the cavity was dominated by the dispersion of the transmission materials (MgO:PPLT, CaF_2, and N-SF11 glass). The thickness of the CaF2 lens was 2.7 mm and the pass length in the N-SF11 prism was approximately 8 mm. The GDD values were 567, -3.7, and, 246 fs^2 for MgO:PPLT, CaF_2, and N-SF11, respectively. Therefore, the total GDD was 809 fs^2. This spectral dispersion was compensated for by using a fused silica (SiO_2) plate with an AR coating. Fig. 4(a) shows the group indices of the transmission materials ($n_g(\lambda)$). The plotted values represent the difference from the value at $\lambda_0 = 1580$ nm. The total dispersion was evaluated as a summation of group indices multiplied by their lengths, that is, $\Sigma\{n_g(\lambda) - n_g(\lambda_0)\}L$, where L is the length. The length of the SiO_2 plate was determined to be 24 mm to compensate for the total dispersion. Fig. 4(b) depicts the total dispersions with and without the SiO_2 plate.

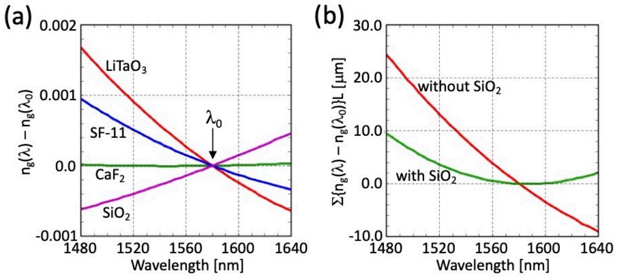

Fig. 4. (a) Group indices of transmission materials in the SPOPO cavity as a function of the wavelength. (b) Total dispersion of transmission materials in the SPOPO cavity.

The pump beam was linearly focused in the horizontal direction using a cylindrical lens with a focal length of 200 mm. A wide region in the MgO:PPLT was pumped and broad spectral components of the signal light were generated in this line-focus setup.

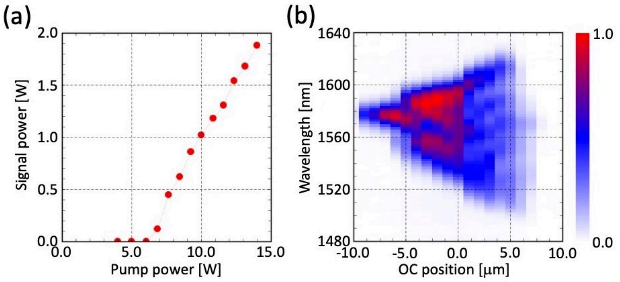

Fig. 5. (a) Signal output power as a function of pump power when the OC position is zero. (b) Contour plot of the signal spectra as a function of the OC position when the pump power is 14.0 W.

Fig. 5(a) depicts signal output power as a function of the pump power. The OC position was determined to maximize the signal output power and this position was defined as the origin of the OC position. The threshold pump power was approximately 7 W. The slope efficiency was approximately 20% in the pump power range over 10 W. Fig. 5(b) shows a contour plot of the spectra as a function of the OC position when the pump power was 14.0 W. The figure shows that the spectra expand with an increase in the OC position. The spectral width was approximately 80 nm at the OC position of 0.0 and 120 nm at the OC position of 5.0 μm. The broadband oscillation was observed in a wider range of the OC position with an increase in the pump power.

The pump pulse length (FWHM) was measured as 392 fs using the SHG-FROG (frequency-resolved optical gating) measurement. The signal pulse length was 81 fs from the SHG-FROG for the line-focus setup with a pump power of 14 W and the OC position at zero. This length was approximately 1/5 of the pump pulse length. It was observed that the signal pulse length was the shortest when the OC position was near zero. Furthermore, when the OC position was over zero, the spectrum became broader, but the pulse length did not decrease.

In conclusion, the broadband operation of SPOPO with a spatially dispersed beam was demonstrated. Additionally, signal pulses with a pulse length of approximately 1/5 of the pump pulse length were generated.

Acknowledgments

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