High-performance cavity-phase matching by pump reflection

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Since cavity-phase matching has been experimentally realized, the efficiency is limited to 20%. In this Letter, we successfully achieved a conversion efficiency as high as 41% with a slope efficiency of 48.5% using cavity-phase matching, by reflecting the pump beam at the end surface of the $KTiOPO_4$ crystal. The high performance of the device makes it a promising candidate to substitute for quasi-phase-matching material.

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It is well known that the phase-matching condition is one of the key problems in nonlinear optics. Quasi-phase matching (QPM) in an optical superlattice (OSL) [1,2] is a widely used technique to make efficient frequency conversion possible, in applications such as beam and pulse shaping, multiharmonic generation, all-optical processing [3], and the generation of entangled photons [4]. However, limited by the fabrication technique, most QPM materials are ferroelectric crystals [such as $LiNbO_3$ (LN), $KTiOPO_4$ (KTP), etc.] with an aperture of less than 2 mm. Different from QPM, cavity-phase matching (CPM) has been predicted [5] in the 1960s, but was not experimentally realized until 2011 by Xie *et al.* [6], whose work features some unique spectral characteristics of CPM such as a single longitudinal mode and narrow linewidth. In CPM, phase mismatch is compensated for by resonant recirculation in the cavity, which means that forward passing light and reflected light are in phase after every cycle. From a different perspective, a nonlinear sheet in CPM is imaged periodically in space to achieve phase matching. The fabrication process of CPM material includes polishing and coating but not the electric field poling technique, making nonferroelectric crystals (such as BaB_2O_4, LiB_3O_5, quartz, etc.) available in CPM. At the same time, the aperture is only limited by the polishing process, which today can be several centimeters [7]. In previous works, degenerate and nondegenerate parametric downconversion have been realized using CPM in KTP and LN [8]. Limited by the small nonlinear coefficient and thickness, the reported efficiency is no more than 20%. In this Letter, we dramatically increase the conversion efficiency and slope efficiency to 41% and 48.5%, respectively, by reflecting the pump beam at the end surface of the CPM crystal. Meanwhile, the reflecting pump beam leads to nonlinear interference when temperature is tuning, and the tuning curve splits into two peaks with doubled efficiency.

In the CPM represented before, the parametric process only exists in the forward direction because of the single pass of the pump beam [6]. In our experiment, the end surface of CPM is coated with high-reflectivity film at the pump wavelength; therefore at the backward direction the reflecting pump converts into parametric signal and idler light, too. If the forward and backward parametric light are in phase, the interference of the two processes causes efficiency to be enhanced [9]. If they are not in phase, the signal and idler waves will convert back into a pump wave due to destructive interference.

According to the coupled wave equation [10], the pump and signal can transform backward from one to the other depending on their relative phase. The phase mismatch ϵ after the reflection can be expressed as

$$\epsilon = \Delta k \cdot L - \Delta\varphi, \tag{1}$$

where $\Delta\varphi = \varphi_p - \varphi_s - \varphi_i$, φ_p, φ_s, φ_i represents the phase shifts of the pump, signal, and idler at the end surface, respectively. $\Delta k = k_p - k_s - k_i$ is the phase-mismatch wavevector. L is the length of the cavity. To precisely control the phase shift of the pump, signal, and idler at the output surface, we designed an alternate periodic structure of SiO_2 and ZrO_2 as a metallic-like dielectric coating. From the calculated result in Fig. 1, we can see that the coating will cause a phase shift of π for wavelength near 532 and 1064 nm after each pump reflection. On the other hand, if the output wavelength has a deviation of 50 nm from 1064 nm, then the phase shift will change linearly from π to zero. As a result of phase mismatching, the conversion efficiency will surely drop, which is shown in Fig. 3.

Because of the reflection of the pump, a parametric process will occur between the three waves after the reflection. When $\epsilon = 2n\pi$, the waves that are generated before and the ones generated after the reflection are in phase, which leads to constructive interference

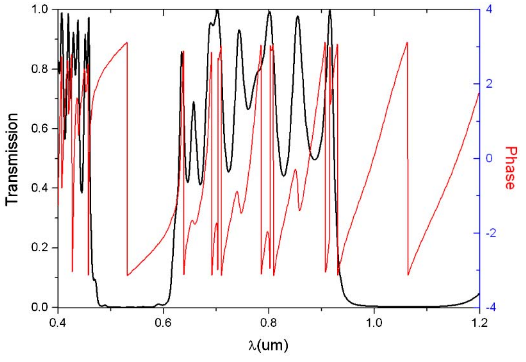

Fig. 1. Calculated transmission and phase shift as a function of wavelength.

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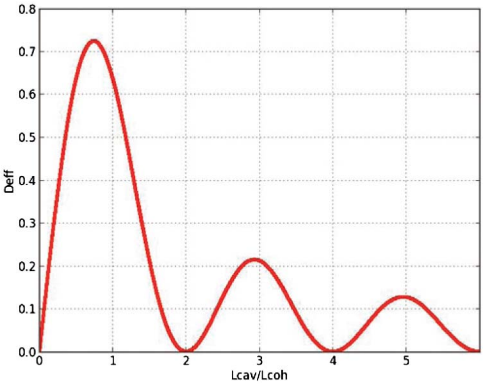

Fig. 2. Effective nonlinear coefficient varies as a function of $L_{\text{cav}}/L_{\text{coh}}$, where the reflection on the output surface causes π difference in phase.

between them. The equivalent interaction length would be doubled compared with the no-pump-reflection situation. Conversely, the interference will become destructive if $\epsilon = (2n+1)\pi$ [9]. Taking $\Delta\varphi$ into consideration, the effective nonlinear coefficient [10] can be expressed as follows:

$$d_{\text{eff}} = d\left|\operatorname{sinc}\left(\frac{\pi L}{2l_c}\right)\sin\left(\frac{\pi L}{2l_c}\right)\right|. \tag{2}$$

In our study, we keep $L_{\text{cav}} \le L_{\text{coh}}$ to achieve efficient CPM. From Fig. 2 we can see that the most efficient process happens where $L_{\text{cav}} = 0.72L_{\text{coh}}$. The end surface's film is designed to make $\epsilon = 2\pi$ at that point.

The sheet optical parametric oscillator (SOPO) used in our study is made up of x-cut KTiOPO$_4$ (KTP) crystal. We choose type-II phase matching where the pump, signal, and idler beams have polarization along the y, z, and y axes, respectively. The SOPO has a designed thickness of 200 μm along the x axis and a surface area of 2 mm × 2 mm. From the mode interval of longitude we measured, we calculated that the thickness of SOPO is 198.6 μm. The current polishing technique can control the cavity thickness error in 5 μm. According to the theoretical calculation, this precision should be 0.1 μm if we want exactly the same output wavelength. But we can tune the pump wavelength or temperature to achieve approximately the same wavelength from each sample in the current condition. The input surface of KTP is antireflection coated for 532 nm and high reflection for 1000–1100 nm, where $R = 99.8\%$. The output surface is coated $R = 99.8\%$ for 532 nm and $R = 98.0\%$ for a beam ranging from 1000 to 1100 nm. In this SOPO the pump light will be reflected once in every cycle, while the signal and idler will be constrained in the cavity.

In our experiment, the SOPO was pumped at 532 nm by a single-longitudinal-mode laser, whose pulse duration is 5 ns and repetition rate is 10 Hz. We operated the relative phase of the pump, signal, and idler by controlling the temperature of the SOPO in an oven with accuracy of 0.01°C. The Sellmeier equation of KTP [11] can be shown as follows:

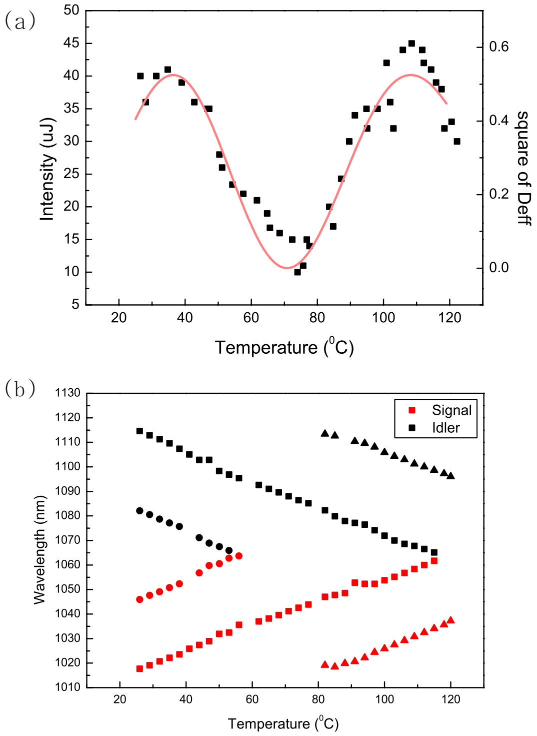

Fig. 3. (a) Measured output energy as a function of temperature while the pump is 150 μJ. (b) Output wavelength depending on the temperature.

$$n_i^2 = A_i + \frac{B_i}{\lambda^2 - C_i} - D_i\lambda^2, \qquad (i = x, y, z). \tag{3}$$

The temperature correction is

$$\Delta n(\lambda, t) = n_1(\lambda)(t - 25°\text{C}) + n_2(\lambda)(t - 25°\text{C})^2. \tag{4}$$

From the equations above, we calculated how the effective nonlinear coefficient changes over the temperature of SOPO. Since the output intensity is proportional to the square of d_{eff} [10], we can roughly show the tendency of output intensity, as in Fig. 3(a). We also measured the output wavelength at a different temperature as shown in Fig. 3(b). The SOPO showed an output wavelength tuning range of 40 nm, while the temperature varied from 25°C to 110°C. As the output wavelength deviated from 1064 nm, the corresponding conversion efficiency dropped. The measured output energy peaked at 40°C and 110°C, where $l_{\text{coh}} = 300$ μm. $l_{\text{cav}}/l_{\text{coh}} = 0.667$ corresponding to the first peak in Fig. 2. At 70°C, the $l_{\text{coh}} = \infty$, which means that this is a birefringent phase-matching (BPM) point. In our previous reports, the CPM with a single-pass pump will reach the conversion peak at this point. But in the case with constructive pump reflection, as shown in Fig. 3, at this point the output decreases to nearly zero for $\epsilon = 3\pi$.

As shown in Fig. 4, the wavelength of the signal and idler can be tuned by controlling temperature. From measured data, we can see that the signal was tuned in a range of 43.3 nm when the temperature varied from 39.00°C to 112.02°C. At 112.02°C as in Fig. 4, the signal and idler are near frequency degenerate with a wavelength

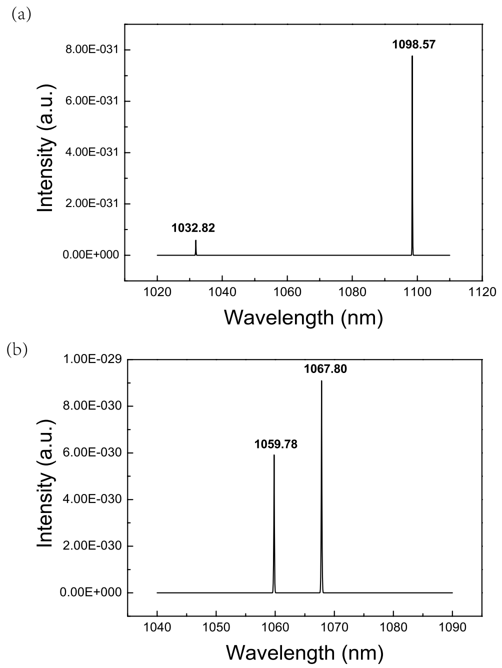

Fig. 4. Wavelength of signal and idler at temperature of (a) 43° C and (b) 112°C, respectively.

difference of about 8 nm. Since their polarizations are orthogonal, they can be applied to generate terahertz through difference-frequency generation (DFG) in GaSe [12]. We also measured the output energy at the temperature of 43°C, where the signal and idler are 1098.57 and 1032.82 nm, respectively. From Fig. 5, we can calculate that the SOPO oscillated at a threshold of 21 μJ while the waist of the pump beam was 150 μm. The highest conversion efficiency of 41.05% occured when the pump was 190 μJ. The slope efficiency is 48.56%. Compared with the method in which the pump passes forward, where the slope efficiency is 21.2% [6], we have nearly doubled the conversion efficiency and slope efficiency. By increasing the waist of the pump beam, we can improve the pump energy to the submillijoule level without damaging the crystal, while the beam quality drops a little.

In conclusion, we experimentally realized CPM with conversion efficiency as high as 41% and slope efficiency of 48.5%. The highest conversion peak is located at 40°C

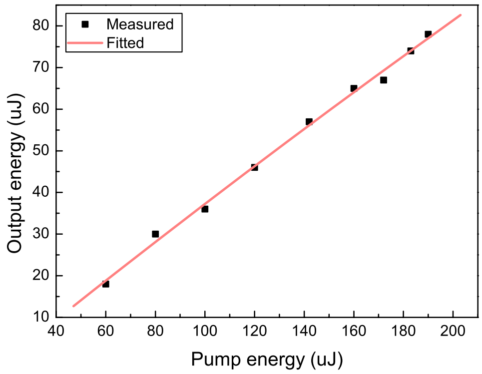

Fig. 5. Measured output energy as a function of the pump energy at 43°C.

and 110°C, and back conversion is observed at the BPM point. With lower threshold and higher efficiency, this technique will make nonferroelectric crystals suitable for CPM.

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