Ultrabroadband optical parametric chirped-pulse amplifier using a fan-out periodically poled crystal with spectral spatial dispersion

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Based on the full two-dimensional characteristics of the quasi-phase-matched fan-out periodically poled crystal, a scalable and engineerable scheme for ultrabroadband optical parametric chirped-pulse amplification is proposed, which can significantly broaden the gain bandwidth by the spatial separation of different frequency components of the signal pulse and manipulation of the distribution of the pump beam along the fan-out direction of the crystal. The theoretical analysis shows that the signal pulse can be amplified with minimal spectrum narrowing, and the initial spectrum can be broadened considerably if needed. Based on this scheme, using a fan-out periodically poled 5% mol MgO-doped congruent lithium niobate with a configuration of 5 × 0.5 × 5 mm^3 and two pump beams, the 3.3-μm middle-infrared ultrabroadband optical parametric chirped-pulse amplifier is designed. The numerical computation results confirm that the −3 dB gain bandwidth of this amplifier exceeds 320 nm and can be further broadened.

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I. INTRODUCTION

The developments in many fields, ranging from high-order harmonic generation and the generation of soft x rays to the probing of ultrafast processes in physics, chemistry, electronics, and biology, have increased the demand for extremely high power and ultrashort laser pulses. Until now, optical pulses in the sub-10-fs range were produced by a variety of methods [1]. To amplify these ultrashort pulses and preserve their duration, the gain bandwidth of the amplifier must exceed the bandwidth of the input pulse. Because of its primary advantages of high contrast ratio, broad spectral bandwidth, and low cost, the optical parametric chirped-pulse amplifier (OPCPA) has been successfully used to replace the conventional regenerative amplifier in chirped-pulse amplification laser systems [2]. Many schemes of ultrabroadband OPCPA had been proposed, including a noncollinear scheme [3–7], a degeneracy scheme [8–11], and schemes using a properly diverged pump beam or several pump beams [12–14], as well as using several pairs of nonlinear optical crystals [2]. The OPCPAs that employ quasi-phase-matched (QPM) nonlinear periodically poled crystals have many advantages [10,15], and the noncollinearity-induced modification of the retracing behavior of the parametric tuning curves close to degeneracy was theoretically investigated and experimentally demonstrated with the aim of increasing the parametric amplification bandwidth in periodically poled crystals [15,16]. Gao [17] reported that the difference frequency generation bandwidth of sinusoidally chirped periodically poled $LiNbO_3$ is about twice that of uniform gratings. In addition, although the fan-out periodically poled crystal is typically thought of as a continuously varying one-dimensional QPM structure, several two-dimensional (2D) QPM structures and their applications in optical parametric interactions have been discussed [18–21].

In this paper, based on the full 2D characteristics of the fan-out periodically poled crystal, a scalable and engineerable ultrabroadband OPCPA with a new degree of freedom for enhancing the bandwidth is proposed, which changes the ultrabroadband OPCPA into a series of wide continuous narrow-band QPM OPCPAs by means of spectral spatial dispersion and multiple pump beams. The theoretical analysis and numerical computation show that the proposed OPCPA can expand the bandwidth for dozens of times more than that of the uniform periodically poled crystal in the same conditions. Thereby, this OPCPA scheme can serve as the basis for a broadband amplifier and sum (or difference) frequency generation of a broadband pulse and a narrow-band pulse. An ultrabroadband 3.3-μm middle-infrared (mid-IR) OPCPA based on this scheme has been designed and investigated, which can be scalable to higher energies.

II. THEORETICAL ANALYSIS

We assume that the chirped signal pulse and the pump pulse are rather long, so that the group-velocity mismatch between the pump and signal (idler) pulses in a short nonlinear crystal can be neglected. The gain bandwidth of this OPCPA, based on the uniform periodically poled crystal, can be estimated by using the analytical solution of the coupled wave equations in the slowly varying envelope approximation and by assuming the pump pulses have flat-top spatial and temporal profiles. In the case of negligible pump depletion and transverse effects, the intensity small signal gain $G_s(L)$ of the amplified signal pulse of OPCPA can be given [22,23]

$$G_s(L) = \frac{I_s(L) - I_s(0)}{I_s(0)} = \Gamma^2 \sinh^2(\gamma L)/\gamma^2, \qquad (1)$$

where $\gamma = \sqrt{\Gamma^2 - 0.25\Delta k^2}$, $\Gamma^2 = 8\pi^2 v_s v_i d_{\text{eff}}^2 I_p / (\varepsilon_0 c^3 n_p n_s n_i)$, $\Delta k = 2\pi(n_p v_p - n_s v_s - n_i v_i - c/\Lambda)/c$. Here Γ is the parametric gain coefficient, Δk is the wave-vector

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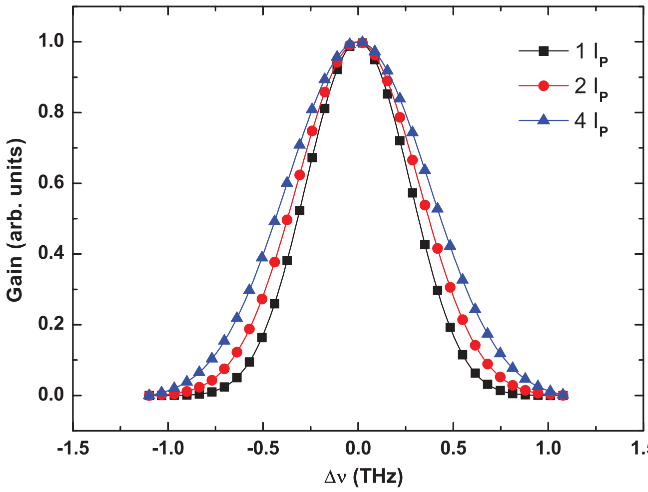

FIG. 1. (Color online) The gain profiles of OPCPA for different pump intensity.

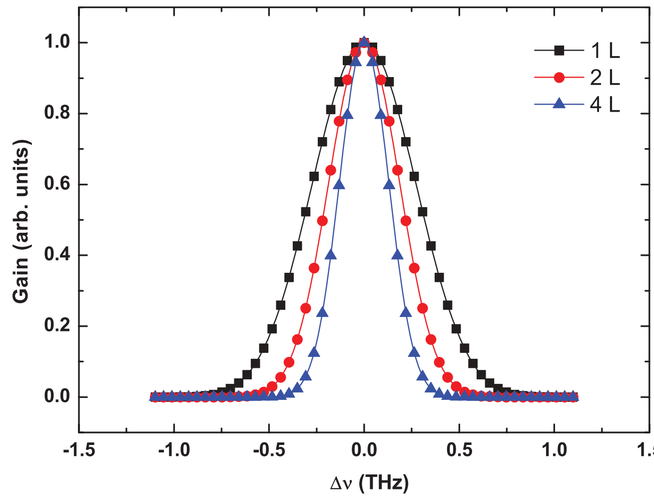

FIG. 2. (Color online) The gain profiles of OPCPA for different crystal length.

mismatch, L is the crystal length, $d_{\rm eff}$ is the effective nonlinear coefficient, Λ is the poled period of crystal, I_p is the pump intensity, $v_{p,s,i}$ are the pump, signal, and idler frequencies, respectively, and $n_{p,s,i}$ are the pump, signal, and idler refractive indices, respectively. For $\Gamma L \gg 1$ and $\Delta k \ll \Gamma$, we have

$$G_s(L) \cong 0.25 \exp[(2\Gamma - (\Delta k)^2/4\Gamma)L]. \tag{2}$$

Here we assume that the spectral bandwidth of the pump pulse is narrow enough that the pump pulse can be treated as a monochromatic wave. According to the energy-conservation condition $v_p = v_s + v_i$, any detuning δv of the signal frequency is accompanied by a shift of the idler frequency by an amount $-\delta v$. The gain profiles of OPCPA for different pump intensities and crystal lengths are calculated and shown in Figs. 1 and 2, respectively. From Figs. 1 and 2 we find that the bandwidth of OPCPA will broaden as the pump intensity increases or the length of crystal decreases. For the fixed pump intensity and crystal length, the gain bandwidth of OPCPA depends on the material dispersion and the beam propagation geometry [15]. Because the grating period of nonlinear crystal is designed according to the pump wavelength and the signal (idler) central wavelength with collinear geometry, if we neglect higher-order dispersion, when $\Delta k = 2(\ln 2\Gamma/L)^{1/2}$, the -3 dB gain bandwidth Δv of OPCPA is given by

$$\Delta v = 0.53\,|u_{si}|\,\sqrt{\Gamma/L} \quad (u_s \neq u_i), \tag{3}$$

or

$$\Delta v = 0.58|g_s + g_i|^{-1/2}(\Gamma/L)^{1/4} \quad (u_s = u_i), \tag{4}$$

where $u_{si} = u_s u_i/(u_s - u_i)$, and u and g are the group velocity and group-velocity dispersion of the waves labeled by the appropriate subscripts [24]. For example, in the parameter conditions listed in Table I, here n_s, n_i, n_p, and $d_{\rm eff}$ are calculated according to Ref. [25]. The -3 dB gain bandwidth Δv of OPCPA using the uniform grating periodically poled 5% mol MgO-doped congruent lithium niobate (PPMgLN) is 0.46 THz.

From $\Delta k = 2\pi(n_p v_p - n_s v_s - n_i v_i - c/\Lambda)/c$, we find that if the spectral components of the signal beam can be separated completely and amplified, respectively, by the different QPM amplifiers with different crystals of appropriate poled period Λ, the Δk of every amplifier will be equal to 0, and all spectral components of the signal beam will have the same gain when the pump intensity and crystal length of the amplifiers are identical; the signal gain bandwidth can be significantly increased. However, because the amplifier has a certain gain bandwidth, it is not necessary to completely separate the spectral components, nor to use so many amplifiers, if we replace the uniform grating periodically poled crystal by a fan-out periodically poled crystal. By using the spatially chirped signal beam and the highly elliptical pump beam, we can also obtain the same signal gain bandwidth, whereas the change of the gain is almost not noticeable. This ultrabroadband OPCPA is shown schematically in Fig. 3. The incidence signal beam passes through a grating-lens pair and becomes a spatially chirped beam. The pump and signal beams are combined to three elliptical spots on the incidence face of the crystal using a dichroic mirror, and are temporally synchronized. The pump beams can be gradually shifted along the fan-out direction of the crystal (x axis), and at the same time, remain parallel to each other and overlap with the signal beam; the elliptic partly overlapped spot of the pump beams is slightly larger than that of the signal beam in the crystal. The grating-lens pair can be replaced by a grating pair or Brewster-angled prism pair or other optical scheme with the same function.

Now, the spectral components of the signal beam have been spatially dispersed along the x axis (see Fig. 3). As a result, the x dimension of the beam will be expanded from Φ_0 to Φ_C, each

TABLE I. The parametric values of OPCPA using uniform grating.

Parameter	Value	Parameter	Value
I_p	2 GW/cm^2	$d_{\rm eff}$	15 pm/V
n_s	2.292	n_i	2.26
n_p	2.248	λ_i	1549 nm
λ_s	3300 nm	λ_p	1054 nm
L	0.5 cm	T	400 K

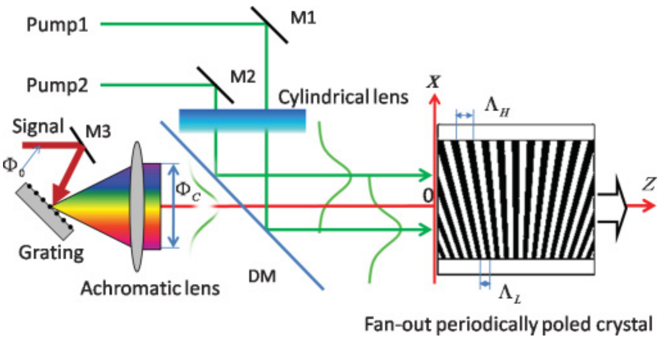

FIG. 3. (Color online) Schematic diagram of ultrabroadband OPCPA using fan-out PPMgLN with spatially chirped signal beam and two pump beams.

spectral component of the parallel laser pulse will propagate along the longitudinal direction of the crystal (z axis), and the different wavelengths are amplified in the different transverse regions of the crystal. Such a spatially dispersive amplification gives rise to the generation of a broad continuous output spectrum. We may consider the region where the pulse crosses the cell as consisting of N neighboring "channels" ($N = \Phi_C/\Phi_0$), each one having a spatial width of Φ_0 and containing a spectrum with a bandwidth of $\Delta v' = 2\Delta v_s/N$; here Δv_s is the full-width-at-half-maximum (FWHM) signal bandwidth.

As shown in Fig. 3, from one edge of the nonlinear crystal to the other, the QPM grating period varies linearly (may also vary nonlinearly if needed) from Λ_L to Λ_H and the ferroelectric domain ratio is a 50:50 duty cycle. By use of a suitable design of the grating period from Λ_L to Λ_H according to the QPM condition at a given temperature, in each channel the spectral bandwidth is satisfied, $\Delta v' \leqslant \Delta v$ (-3 dB gain bandwidth of OPCPA using uniform grating crystal) if N is big enough. Thereby, the ultrabroadband OPCPA can be regarded as N narrow-band QPM OPCPAs with a continuously varying grating period. Because in each channel the center wavelength fully satisfies the QPM condition and the wave-vector mismatch $\Delta k'$ is very small, the gain G' of the mth channel is nearly constant over the bandwidth $\Delta v'$ and can be given by Eq. (2) as well.

As long as variable Γ depends strongly on the pump intensity I_p, if the pump intensity is the same in each channel, this OPCPA composed by the N channels will have an identical gain over the whole spectrum of $2\Delta v_s$, which is much broader than the gain bandwidth of OPCPA using the uniform grating periodically poled crystal. In addition, we can also use two or more pump beams to control the gain of the particular channels or regions, and, therefore, the gain of the spectrum centered at these channels or regions by separately adjusting their intensity and position. In particular, we can compensate for frequencies at the spectrum wings by adding a pump pulse in the corresponding spatial regions.

III. DESIGN AND ANALYSIS OF MID-IR ULTRABROADBAND OPCPA

The laser pulse wavelength regime above 3 μm is of particular importance for spectroscopic applications [26],

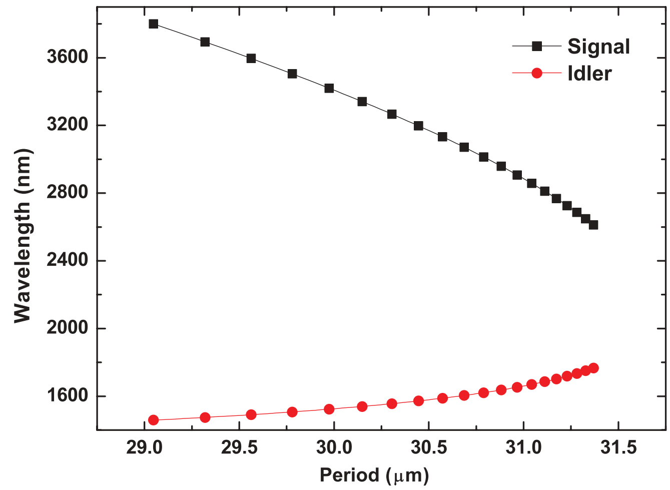

FIG. 4. (Color online) Dependence of the mid-IR signal wavelength on the grating period of fan-out PPMgLN for type-0 QPM at temperature 400 K.

the interaction of atoms with intense field lasers [27], high harmonic generation [28–31], and gas sensing [32,33]. The mid-IR ultrashort pulse with lower energy in the sub-100-fs) range can be produced [26,34–36]. However, it is more challenging to obtain high-energy sub-100-fs pulses in the mid-IR wavelength range. Based on the large aperture fan-out PPMgLN, a scalable high-energy ultrabroadband OPCPA for 50-fs 3.3-μm mid-IR pulse amplification is designed and investigated.

A. Parameter design

The nonlinear crystal is a PPMgLN with a configuration of $5\times0.5\times5$ mm^3 in the x (wide), y (thick), and z (long) directions, respectively. For the type-0 QPM ($e \rightarrow e + e$) condition, the dependence of the mid-IR signal wavelength on the grating period of fan-out PPMgLN pumped by the 1054-nm laser pulse at temperature 400 K is calculated and shown in Fig. 4 using the nonlinear optics' software SNLO (available from A. V. Smith, AS-Photonics, Albuquerque, NM). From Fig. 4, we can find that the varying curve of the grating periods is nearly linear in the wave range of 2.9 to 3.8 μm. Thereby, the fan-out periodically poled grating periods can be designed to linearly vary from 30.8 to 29.5 μm continuously across the x axis for amplification mid-infrared signal pulse from 2.98 to 3.62 μm. The crystal was placed in an oven and operated at 400 ± 0.1 K.

For generalization, we assume that both signal and pump pulses are Gaussian shape in time and in space. The 3.3-μm signal beam with a FWHM waist of 50 μm propagates through the grating-lens pair (the grating groove spacing is 320 mm^{-1} and the focal length of the achromatic lens is 25 mm) and becomes an elliptic spatial chirped-beam with a spot size of 2500×50 μm^2 (FWHM) in the x axis and y axis, respectively, thus we have $N = 50$. The 50-fs, 3.3-μm, 1-kHz mid-IR signal pulses, of which the FWHM spectral bandwidth reaches up to 320 nm (8.8 THz), are temporally stretched to 50 ps by a stretcher. Temporal stretching is applied in order to optimize the temporal overlap between the pump and signal pulses and thus the gain bandwidth [36].

We assume that υ_x is the center frequency at position x. In this design, the FWHM positions of the signal pulse spectrum are symmetrically set at $x = \pm 1250\ \mu$m by shifting the signal beam along the fan-out direction of crystal. Thus we have $\upsilon_x = \upsilon_0 + 4.4x/1250$ or $\Delta\upsilon_x = \upsilon_x - \upsilon_0 = 4.4x/1250$ (THz).

The OPCPA is pumped by 2-mJ, 74-ps, 1054-nm, 1-kHz pulses from a regenerative amplifier. The pump beam is split into two replicas. Then, using a cylindrical lens with a focus length 15 cm, the two replicas are focused to two spots with a size of $60 \times 2500\ \mu\text{m}^2$ (FWHM) elliptic spatial shape in the x axis and y axis, respectively. The pump and signal beams are combined on the incidence face of a crystal using a dichroic mirror. The time delays between the pump and signal pulses can be separately fine tuned with two optical delay lines for the precise temporal overlapping and flat spectral gain profile. When the delay between the two pump-pulse peaks is adjusted to be about 50 ps, the pump-to-signal pulse duration ratio is about 2, and the bandwidth narrowing effect caused by the temporal shape of the pump pulse can be neglected [23].

If we use the same parameters listed in Table I, the -3 dB gain bandwidth ($\Delta\upsilon$) of each channel is 0.46 THz as well, while $\Delta\upsilon' \approx 2\Delta\upsilon_s/N = 17.6/50 = 0.352$ THz, which is satisfied by $\Delta\upsilon' \leqslant \Delta\upsilon$. Thus, in each channel, the wave-vector mismatch $\Delta k'$ is very small and $\Delta k' \ll \Gamma$. Therefore, $G_s(x,y,L)$ of the different spectrum components at different channels depends on the pump intensity $I_p(x,y)$, and can be given as

$$G_s(x,y,L) \cong 0.25 \exp\{2\Gamma[I_p(x,y)]L\}. \tag{5}$$

B. Gain bandwidth characteristics

On the incidence face of a fan-out crystal, the spatial shape of the pump and signal intensity can be given as

$$I_p(x,y) = I_0 \exp\left[-2\left(\frac{x-x_b}{w_{px}}\right)^2 - 2\left(\frac{y}{w_{py}}\right)^2\right] + I_0 \exp\left[-2\left(\frac{x+x_b}{w_{px}}\right)^2 - 2\left(\frac{y}{w_{py}}\right)^2\right], \tag{6}$$

and

$$I_s(x,y) = I_{s0} \exp\left[-2\left(\frac{x}{w_{sx}}\right)^2 - 2\left(\frac{y}{w_{s0}}\right)^2\right], \tag{7}$$

where $w_{px} = 2500/\sqrt{\ln 4}$, $w_{py} = 60/\sqrt{\ln 4}$, $w_{sx} = 2500/\sqrt{\ln 4}$, and $w_{s0} = 50/\sqrt{\ln 4}$, respectively. When $x_b = 1050\ \mu$m, the intensity spatial shape of the two overlapped pump beams is mostly flat at the x axis. The spectral intensity shape of the signal beam on the incidence face of a fan-out crystal changing with $\Delta\upsilon_x$ can be given as

$$I_s(\Delta\upsilon_x,y) = I_{s0} \exp\left[-2\left(\frac{285\Delta\upsilon_x}{w_{sx}}\right)^2 - 2\left(\frac{y}{w_{s0}}\right)^2\right]. \tag{8}$$

In order to compare the gain bandwidth characteristic between both OPCPAs pumped by two beams or one beam, we assume that the spatial intensity shape of the one-pump beam is given as

$$I'_p(x,y) = I_0 \exp\left[-2\left(\frac{x}{3000/\sqrt{\ln 4}}\right)^2 - 2\left(\frac{y}{w_{py}}\right)^2\right], \tag{9}$$

where the beam waist (FWHM) is 3000 μm at the x axis for the better trade-off between the efficiency and bandwidth of OPCPA.

According to Eqs. (5)–(9), the spatial mapping of the spectral gain of the mid-IR OPCPA pumped by two or one Gaussian beams has been calculated and shown in Figs. 5 and 6, respectively. In order to facilitate observation and understanding for the identical pump peak intensity and crystal length, the gain bandwidth profiles of the different OPCPAs are calculated and shown in Fig. 7, which include the OPCPAs using fan-out PPMgLN pumped by one or two Gaussian beams, and that using uniform PPMgLN pumped by one flat-top beam with a fully flat intensity profile over the spatially overlapped region between the pump and signal beam (the pump intensity is identical, and is equal to I_0 here), respectively. Obviously, the FWHM gain bandwidth of the OPCPA using fan-out PPMgLN is much broader than that using uniform PPMgLN, and the FWHM gain bandwidth of the OPCPA using fan-out PPMgLN pumped by two beams is broader than that pumped by one beam.

The output spectrum profiles of the different mid-IR OPCPAs at $y = 0$ are calculated and shown in Fig. 8, which includes the OPCPAs using uniform PPMgLN and fan-out PPMgLN pumped by the same flat-top beam, and that using fan-out PPMgLN pumped by two or one Gaussian beam, respectively. From Fig. 8, we can find easily that, in the case of same crystal length and peak pump intensity, the FWHM output bandwidth of the OPCPA using fan-out PPMgLN pumped by two Gaussian beams is about 8 THz,

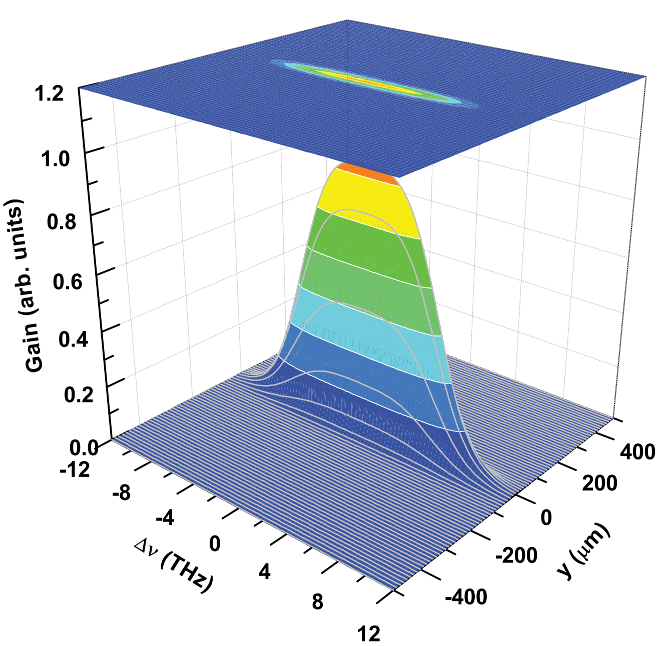

FIG. 5. (Color online) Spatial mapping of the spectral gain of the mid-IR OPCPA pumped by two Gaussian beams for the identical pump peak intensity.

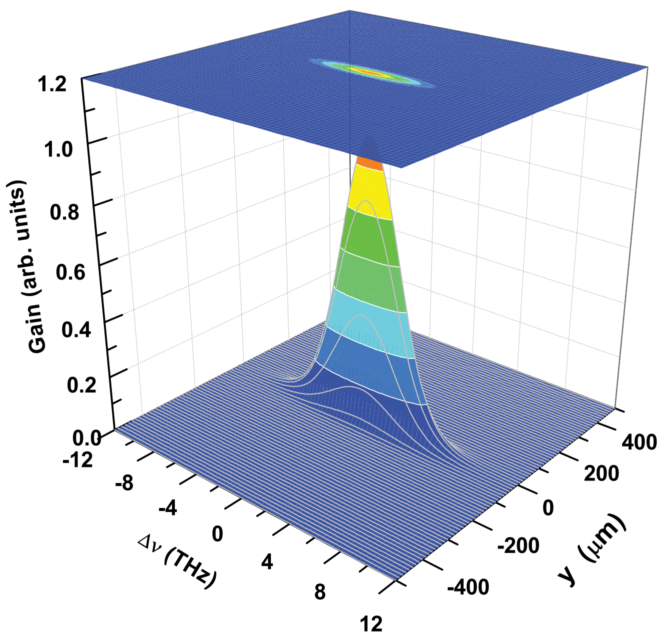

FIG. 6. (Color online) Spatial mapping of the spectral gain of the mid-IR OPCPA pumped by one Gaussian beam for the identical pump peak intensity.

and that pumped by one Gaussian beam is about 4.5 THz. On the other hand, if pumped by the same flat-top beam, the FWHM output bandwidth of OPCPA using fan-out PPMgLN is 8.8 THz while that using uniform PPMgLN is about 0.6 THz. Obviously, the OPCPA using fan-out PPMgLN with a spatially chirped signal beam can greatly broaden the gain bandwidth.

It should be noted that by increasing the width of the crystal and by using a fan-out QPM crystal with a nonlinearly varying grating period, according to the curve of the dependence of the signal wavelength on the grating period shown in Fig. 4, the bandwidth can be further extended. In addition, except for the noncollinear configuration, the other methods for increasing the bandwidth of the amplifier with a uniform periodically poled crystal, such as increasing the pump intensity, degeneracy amplifying, reducing the crystal length, chirped grating period at the longitudinal direction (or tilting placement of fan-out crystal), and so on, can be used for this proposed scheme to further expand the bandwidth.

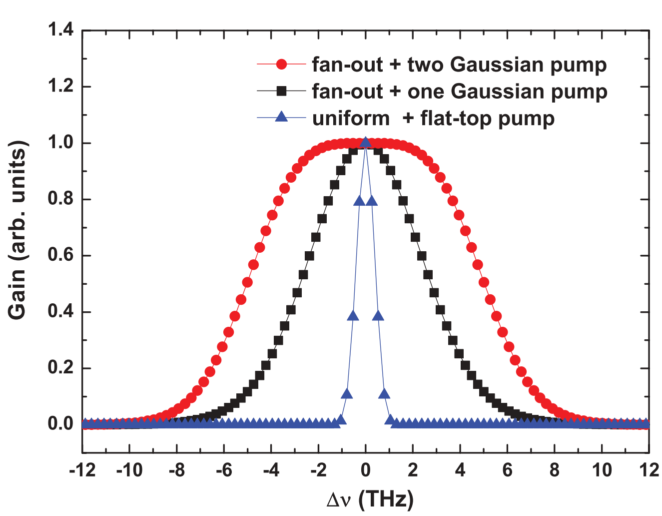

FIG. 7. (Color online) Gain bandwidth profiles of the different OPCPAs for the identical pump peak intensity and crystal length at $y = 0$.

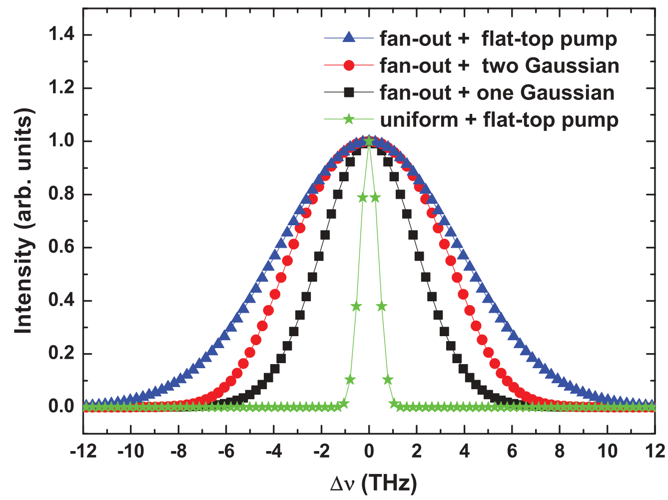

FIG. 8. (Color online) Output spectrum profiles of the different OPCPAs for the identical pump peak intensity and crystal length.

To maximize the gain bandwidth of the OPCPA, the signal beam must fill as much of the crystal aperture. Second, to make the best use of the bandwidth from the signal pulse, the other spectral components beside the central wavelength should be directed into the correct region of the fan-out grating. This can be achieved by changing the focal length of the lens (and also adjusting accordingly the distance of the grating-lens pair) and the center position of the crystal, the fine region adjusting can be obtained by changing the incidence angle of the signal beam. In addition, the optimal values of N and of the other parameters, including the time delays between the pump and signal pulses, the space distance between the two pump beams, and the pump intensity, should be determined by the concrete needs and experiment data.

IV. CONCLUSION

In summary, an ultrabroadband OPCPA has been proposed and discussed. This scheme uses a 2D fan-out periodically poled nonlinear crystal, which enables a large increase in the bandwidth of light produced by this amplifier. The QPM conditions in such a crystal, along with multiple pump beams, creates multiple spatially dispersed narrow-band amplifiers whose gain can be made independent of the signal frequencies being amplified. The poling of the crystal and QPM conditions used in this scheme are in the linear regime but have the potential for modifications and application in the nonlinear regime. Thereby, the gain bandwidth of this OPCPA will only determine the fan-out rate and width of the QPM crystal as well as the pump energy. In addition, because this OPCPA uses a strictly collinear geometry, which can avoid angular dispersion of the broadband signal beam, we thus can obtain excellent beam quality. Therefore, this amplifier can serve as the basis for broadband amplifier and sum (or difference) frequency generation of the chirped broadband pulse and the narrow-band pulse. Based on this scheme, a 50-fs, 3.3-μm mid-IR ultrabroadband OPCPA with two Gaussian pump beams has been designed and investigated, which is very useful for future experimental research.

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