Effect of partial coherence on four-wave mixing in photorefractive materials

Jianhua Zhao,* Xianmin Yi, Xiaonong Shen,† Ruibo Wang, and Pochi Yeh
Department of Electrical and Computer Engineering, University of California at Santa Barbara, Santa Barbara, California 93106
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The effect of partial coherence on four-wave mixing in photorefractive media is studied by taking into account the evolution and propagation of the mutual coherence via a theoretical model. This model is applied to four-wave mixing and two-wave mixing with fully or partially coherent waves. We studied the effect of partial coherence with the presence of all the gratings, and compared the results with those of the transmission grating approximation and of the reflection grating approximation, respectively.

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I. INTRODUCTION

Wave mixing in photorefractive (PR) crystals is a fundamental nonlinear optical process that is responsible for many applications, such as signal processing, optical communications, optical networks, optical computing, etc. [1]. The theoretical study in this area has been focused on wave mixing with monochromatic waves, or waves with full coherence. The effect of partial coherence on wave mixing in PR materials has raised much interest in recent years. One reason is that, in some applications, such as double phase-conjugation [2–4], achromatic volume holography [5], or optical phase conjugation through turbulent media (i.e., sea water or atmosphere) [6], the effect of beam coherence becomes important in the coupling process if the coherence of the beams is limited either by the intrinsic properties of the light source (e.g., beams from two different lasers) or due to the propagation delay (e.g., the path difference between the beams is difficult or impossible to be equalized). Thus, knowledge of the state of coherence during and after coupling is essential in these applications.

Two-wave mixing (TWM) in PR crystals with partially coherent waves has been studied by previous researchers [7–11]. Cronin-Golomb and co-workers [7,8] studied the effect of partially spatiotemporal (three-dimensional) coherence in photorefractive TWM, theoretically and experimentally, and found that the spatial coherence could be improved for amplified and deteriorated for deamplified waves. Bogodaev *et al.* studied TWM with partially spatiotemporal (one-dimensional) coherent waves in transmission grating cases [9]. Yi *et al.* studied contradirectional TWM with partially spatiotemporal (one-dimensional) coherent beams [10,11]. They also studied TWM with partially coherent waves in high speed media [12]. According to these previous works, the coherence of the beams can be improved due to wave mixing. Very recently, Anderson *et al.* developed an operator approach to investigate TWM in a PR medium by viewing the PR media as a ‘‘black box,’’ while the two beams contained the spatially and temporally varying information [13].

There are four gratings recorded in the PR material in the four-wave mixing (FWM) scheme, viz. one transmission grating, one reflection grating, and two $2k$ gratings. FWM is responsible for many modes of phase conjugation (PC) [2–4]. It has many potential applications, e.g., optical interconnecting, laser phase locking, laser beam cleaning, etc. [14–18], because the coherence of the two pump beams is not required. However, in some configurations, it was found experimentally that the performance of FWM is very sensitive to the degree of the mutual coherence of the two pump beams [19]. FWM with partially spatiotemporally coherent waves was studied in a Kerr medium, in which the nonlinearity is fast and can follow the rapid phase changes of the beams [20,21]. However, the nonlinearity of a photorefractive material is much slower than the phase fluctuations of the interacting beams. Therefore, the description of the wave mixing in a PR material is different from that for a Kerr material [7]. The effect of beam coherence in mutually pump phase conjugation (MPPC), without taking into account the coupling and propagation of mutual coherence, was investigated [22,23], and it was found that the performance of the phase conjugate can be decreased or enhanced depending on the contribution of the reflection gratings. FWM with partially (temporal) coherent waves via the transmission grating approximation (TGA) [24,25] and reflection grating approximation (RGA) [26] was recently studied. It was found that the mutual coherence of the signal and the pump beam could be enhanced or decreased depending on the coupling constant and the signal-pump ratio. A low initial mutual coherence could lead to a significant decrease of the phase-conjugate reflectivity PCR [24]. In some cases with pump depletion, partial coherence can lead to an enhancement of the PCR compared to fully coherent waves [25]. The PC beam and the pump beam remain in full coherence during the propagation in TGA, provided that the initial value of the phase conjugate beam is zero [25]. In RGA, at least two variables are needed to describe the second-order statistical properties of the four waves, because the optical path difference between the interfering waves changes significantly as the four waves propagate through the PR medium, and the

*Permanent address: Department of Opto-electronic and Information Engineering, Shandong University, Jinan, Shandong, 250100, China. Email address: jianhua@xanadu.ece.ucsb.edu

†The State Key Laboratory of Crystal Materials, Shandong University, and Department of Physics, Jinan University, Jinan, Shandong, 250100, China.

boundary conditions of the second-order statistical properties (i.e., mutual coherence) are not easily obtained. Results showed that partial coherence always leads to a drop of the signal gain and phase-conjugate reflectivity. But wave mixing can enhance the coherence of the signal beam and the pump beam. The normalized mutual coherence of the PC beam and the pump beam is no longer unity, which is much different from TGA [26]

FWM with partial coherence waves is a very complicated phenomenon. Undoubtedly, the previous investigations through the TGA and RGA can shed much light on how partial coherence affects wave mixing. In fact, when the two pump beams are partially coherent, the transmission grating, the reflection grating, and the $2k$ gratings are always present simultaneously. All the four gratings should be taken into account. Therefore, it is not only very essential, but also very complicated to investigate FWM with partially coherent waves by taking into account all the gratings. And there has been no theoretical model to address this issue to date. In this paper, we proposed a theoretical model and numerically studied the effect of partial coherence on FWM by taking into account the propagation and coupling of the mutual coherence when all the gratings are present. This model can be applied to FWM and TWM with partially coherent or fully coherent waves. The results of the general case are compared with those of TGA and RGA with partially or fully coherent waves.

II. THEORETICAL MODEL

Assuming that all the partially coherent waves have the same central frequency ω_0, all the waves are polarized perpendicular to the plane, and the waves from two pairs of counterpropagation beams with $k_3=-k_2$, $k_4=-k_1$ [see Fig. 1(a)], the coupled wave equations with the slowly varying amplitude approximation [27] can be written as

$$\frac{\partial A_1(z,\omega)}{\partial z}=-\frac{\Gamma_1}{2}\frac{Q_1}{I_0}A_2(z,\omega)-\frac{\Gamma_2}{2}\frac{Q_2}{I_0}A_3(z,\omega)e^{i2\Delta kz}-\frac{\Gamma_3}{2}\frac{Q_3}{I_0}A_4(z,\omega)e^{i2\Delta kz}, \tag{1a}$$

$$\frac{\partial A_2(z,\omega)}{\partial z}=-\frac{\Gamma_1^*}{2}\frac{Q_1^*}{I_0}A_1(z,\omega)-\frac{\Gamma_2}{2}\frac{Q_2}{I_0}A_4(z,\omega)e^{i2\Delta kz}-\frac{\Gamma_4}{2}\frac{Q_4}{I_0}A(z,\omega)e^{i2\Delta kz}, \tag{1b}$$

$$\frac{\partial A_3(z,\omega)}{\partial z}=-\frac{\Gamma_1}{2}\frac{Q_1}{I_0}A_4(z,\omega)-\frac{\Gamma_2^*}{2}\frac{Q_2^*}{I_0}A_1(z,\omega)e^{-i2\Delta kz}-\frac{\Gamma_4^*}{2}\frac{Q_4^*}{I_0}A_2(z,\omega)e^{-i2\Delta kz}, \tag{1c}$$

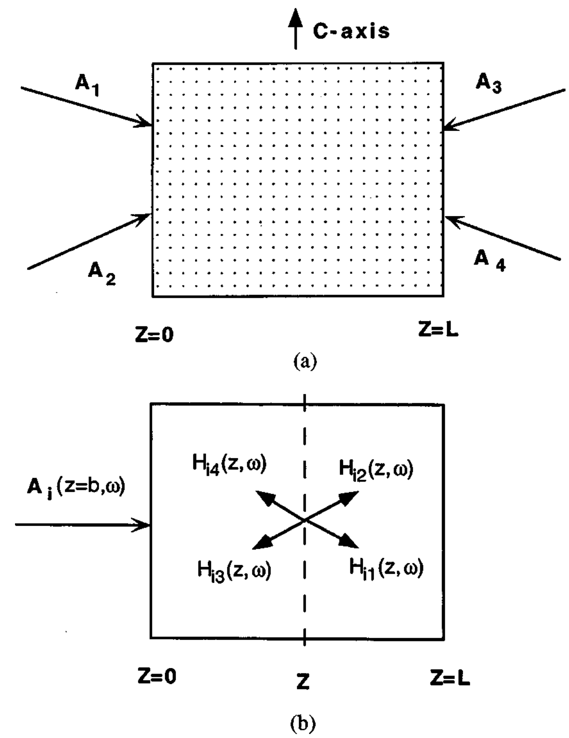

FIG. 1. (a) FWM in a photorefractive medium. We designate A_1 as the signal beam, A_2 as the first pump beam, A_3 as the second pump beam, and A_4 as the phase conjugate beam. (b) Theoretical model for FWM with partially coherent waves. $A_i(z=b,t)$ is the input, $H_{i,j}(z,\omega)$ is the output of the input $A_i(z=b,t)$ at an arbitrary plane in between at position z. $H_{i,j}(z,\omega)$ is regarded as the frequency response of the input at boundary $z=b$, where when $i=1$, 2, $b=0$; $i=3$, 4, $b=L$.

$$\frac{\partial A_4(z,\omega)}{\partial z}=-\frac{\Gamma_1^*}{2}\frac{Q_1^*}{I_0}A_3(z,\omega)-\frac{\Gamma_2^*}{2}\frac{Q_2^*}{I_0}A_2(z,\omega)e^{-i2\Delta kz}-\frac{\Gamma_3^*}{2}\frac{Q_3^*}{I_0}A_1(z,\omega)e^{-i2\Delta kz}, \tag{1d}$$

where Q_i's are the measure of the four gratings recorded in the photorefractive materials, and $I_0=I_1+I_2+I_3+I_4$ is the total intensity of all the beams. Γ_i's are the photorefractive coupling coefficients for transmission, reflection, and $2k$ gratings, respectively. Δk is the phase mismatch between the optical waves and the index grating. The spectral density functions are defined as $E_{i,j}(z,\Delta\omega)=\langle A_i(z,\omega)A_j^*(z,\omega)\rangle$, where $j\geqslant i$ $(i,j=1,2,3,4)$. $i=j$ represents the autocorrelation spectral density function; $i\neq j$ is the mutual correlation density function. In the time domain, the coherence of the four waves is $\Gamma_{i,j}(z,\tau)=\langle A_i(z,t_1)A_j^*(z,t_2)\rangle$, where $i=j$ represents the self-coherence of the four waves, and $i\neq j$ represents the mutual coherence. τ is the time delay, $\tau=t_1-t_2$. Notice that the coherence functions are related to the spectral density functions by

$$\Gamma_{i,j}(z,\tau)=\int E_{i,j}(z,\omega)\exp(-i\omega\tau)d\omega. \tag{2}$$

The intensities and the mutual coherence of the four beams can be obtained easily if assuming the time delay equals zero,

$$I_i(z)=\Gamma_{i,j}(z,0)=\int E_{i,j}(z,\omega)d\omega, \tag{3}$$

$$\Gamma_{i,j}(z,0)=\int E_{i,j}(z,\omega)d\omega. \tag{4}$$

From Eqs. (3) and (4), it is seen that once the spectral density is obtained, one can calculate the intensities and mutual coherent functions.

When the coherent time is substantially less than the relaxation time of the material [28], the dynamic grating amplitudes can be regarded as stationary. Two partially coherent waves with their complex amplitudes fluctuating randomly with time can actually write a stationary grating under appropriate conditions [11]. Thus, the index gratings can be expressed as their ensemble average, given, respectively, by

$$\begin{aligned}
Q_1(z,t)&\cong\langle Q_1(z,t)\rangle=\Gamma_{1,2}(z,0)+\Gamma_{3,4}(z,0),\\
Q_2(z,t)&\cong\langle Q_2(z,t)\rangle=\Gamma_{1,3}(z,0)+\Gamma_{2,4}(z,0),\\
Q_3(z,t)&\cong\langle Q_3(z,t)\rangle=\Gamma_{1,4}(z,0),\\
Q_4(z,t)&\cong\langle Q_4(z,t)\rangle=\Gamma_{2,3}(z,0).
\end{aligned} \tag{5}$$

Note that the grating amplitudes are proportional to the mutual coherence of the four beams at position z, respectively. At stationary states, it is irrelevant to time t. Scattering of partially coherent waves by a stationary grating usually can be modeled by a linear system [29]. Therefore, we can assume that the crystal is a ''black box'' [11,13] in which transmission, reflection, and $2k$ gratings are recorded during four-wave mixing at the stationary state, as shown in Fig. 1(b). If only one incident wave is taken into account, there will be four outputs on any arbitrary plane in between the material. Each output $H_{i,j}(z,\omega)$ can be regarded as the frequency response of the input i in the j direction at position z $(i,j=1,2,3,4)$. Therefore, there are 16 components when all four beams are present. The output in each direction is a combination of the components in that direction, given by

$$A_i(z,\omega)=\sum_{j=1}^{4} H_{j,i}(z,\omega)A_j(z=b,\omega)\quad (i=1-4), \tag{6}$$

where

$$b=\begin{cases}0, & j=1,2\\ L, & j=3,4\ .\end{cases}$$

$A_i(z=b,\omega)$ is determined by the boundary conditions. The output spectral density functions in terms of the four input waves are written as

$$\begin{aligned}
E_{i,j}(z,\omega)=\sum_{\alpha=1}^{4}\sum_{\beta=1}^{4} H_{\alpha,i}(z,\omega)H^{*}_{\beta,j}(z,\omega)\\
\times E_{\alpha,\beta}(z=a,z=b,\omega),
\end{aligned} \tag{7}$$

where

$$a=\begin{cases}0, & \alpha=1,2\\ L, & \alpha=3,4.\end{cases}$$

and

$$b=\begin{cases}0, & \beta=1,2\\ L, & \beta=3,4\ .\end{cases}$$

Equation (7) combines the output spectral functions at position z and the four inputs at their corresponding boundaries.

To obtain the boundary conditions, we assume that all four beams are derived from the same source (e.g., same laser). If the light source is a Gaussian, the normalized spectral distribution of the source would be

$$E_{ss}(\omega)=\frac{4(\pi\ln 2)^{1/2}}{\Delta\omega}\exp\left\{-\left[2\left(\ln 2^{1/2}\frac{\omega}{\Delta\omega}\right]^2\right\}, \tag{8}$$

where $\Delta\omega$ is the full width at half maximum line width of the light source. Assuming the ratio of the pump beam and the signal beam is $\beta_i(\beta_i=I_i/I_1)$, the boundary conditions of the four waves can be written as

$$E_{m,n}(z=a,z=b,\omega)=\sqrt{\beta_m\beta_n}E_{ss}(\omega)e^{-i\omega t_{mn}}, \tag{9}$$

where $t_{mn}=t_n-t_m$ is the time delay of the two waves of m and n arriving at their corresponding entrance planes, $a(b)=0$ for $m(n)=1,2$; $a(b)=L$ for $m(n)=3,4$.

Based on the theoretical model introduced in the preceding section, the effect of partial coherence on four-wave mixing can be studied using an iterative algorithm. The procedure is described as follows.

(i) Provide four arbitrary index gratings, using Eq. (1) to obtain the frequency response of the four waves (e.g., the set of partial differential equations can be solved using the relaxation method, etc. [30]).

(ii) Use Eq. (7) to get the spectral densities of the four waves.

(iii) Fourier transform the spectral densities to get the intensities and the mutual coherence using Eqs. (3) and (4).

(iv) Use Eq. (5) to get new index grating.

(v) Compare the new index gratings with the previous gratings. If the difference between the new gratings and the old ones is acceptable, then the solutions are obtained. Otherwise, continue the above procedures by modifying the index grating correspondingly. In the following calculations, the new version of index gratings obtained in procedure (iv) is used as the input of the new iterations.

From the above procedure, one can see that this system is not only applied to the general case where all the gratings are present, but also applied to transmission grating, reflection grating, and $2k$ gratings with partial or fully coherent waves (e.g., if two pump beams are fully incoherent, then the results should be equal to the transmission grating approximation). These can be realized in the second step to calculate the frequency response. If there are only two inputs, this system can be applied to two-wave mixing with partial or fully coherent waves. We performed calculations of TWM and FWM with fully or partially coherent waves via the TGA and RGA, and found that the previous results can be recovered from this theoretical model. This is a verification of the reliability and applicability of this model. The main concern of this paper is to investigate the effect of partial coherence on FWM in the general case; therefore, we will present the results of FWM when all the gratings are involved and compare these results with those of TGA and RGA in the following section.

III. RESULTS AND DISCUSSION

Using the above model, we studied FWM with partially coherent waves in the general case numerically. This is also a check of the theoretical model. The results are shown in Figs. 2 and 3. In the following calculations, we assume that the initial conditions are the following: the intensity of the signal beam (A_1) is 1, the two pump beams (A_2 and A_3) have the same intensities, and the ratio of pump to signal is β; the phase conjugate beam is 0. And we assume that A_2 and A_1 have no time delay, which means the two waves are fully coherent at the boundary $z=0$. For the convenience of our later discussion, we denote the optical path difference (OPD) as the optical path difference of beam A_1 (or A_2) and beam A_3 at $z=0$. The parameters of the following plots are $\Delta\nu=1.8\times10^9$ Hz, $n=2.3$, $L=1$ cm (n is the refractive index of the material). To compare the effect of the transmission grating and the reflection grating in the process of four-wave mixing with partially coherent waves, we calculate two different cases.

Case 1. Transmission grating is dominant, where $\Gamma_1=-4\ \mathrm{cm}^{-1}$, $\Gamma_2=-1\ \mathrm{cm}^{-1}$, $\Gamma_3=-1\ \mathrm{cm}^{-1}$, $\Gamma_4=-1\ \mathrm{cm}^{-1}$.

Case 2. Reflection grating is dominant, where $\Gamma_1=-1\ \mathrm{cm}^{-1}$, $\Gamma_2=-4\ \mathrm{cm}^{-1}$, $\Gamma_3=-1\ \mathrm{cm}^{-1}$, $\Gamma_4=-1\ \mathrm{cm}^{-1}$.

In the following plots, the solid curves are for case 1, broken curves are for case 2, curves with (without) symbols are for $\beta=100\,(\beta=1)$, respectively. Figure 2 shows the signal gain and the phase-conjugate reflectivity as a function of OPD at $z=0$. It can be seen that when the OPD is very large, the effect of the reflection grating can be neglected, only the transmission grating makes a contribution to the signal gain and the phase-conjugate reflectivity. Figure 2(a) shows that in case 2, the signal gain can be increased due to the presence of the reflection grating, and it increases with the increase of the pump-signal beam ratio. While in case 1, when the pump-signal beam ratio is small, the presence of the reflection grating leads to a small increase of the signal gain. But when the pump-signal beam ratio is large, the presence of the reflection grating leads to a substantial decrease of the signal gain, with respect to the pure transmission grating approximation. In this case, the signal beam is coupled to the direction of the pump beam and the phase conjugate beam during the multiwave coupling process. From Fig. 2(b), we find that in all cases, the presence of reflection grating can enhance the phase conjugate reflectively. In either case, signal gain and PCR can be increased with increasing the pump-signal beam ratio.

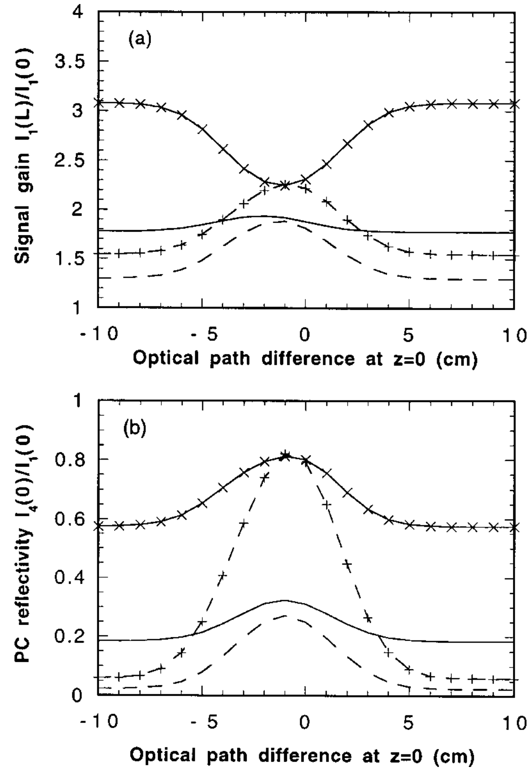

FIG. 2. Signal gain and the PC reflectivity as a function of the optical path difference between the signal beam and the second pump beam at position $z=0$. Solid lines are for the transmission grating dominated case (case 1), broken lines are for the reflection dominated case (case 2). The curves with (without) symbols are for $\beta=100\,(\beta=1)$, respectively. (a) Signal gain; (b) PC reflectivity.

Figure 3 shows the normalized mutual coherence of the four waves at different output planes as a function of the OPD of A_1 and A_3 at $z=0$. Figure 3(a) shows that the mutual coherence of the signal beam A_1 and the first pump beam A_2 remains fully coherent for a large OPD (the initial coherence is assumed to be 1) because no reflection grating is recorded. The presence of the reflection grating has a greater effect on the mutual coherence of A_1 and A_2 in case 2 than in case 1. Increasing the pump-signal ratio can increase the mutual coherence of A_1 and A_2. Take a look at the normalized mutual coherence of A_3 and A_4 [Fig. 3(b)]. In the TGA, we know that A_3 and A_4 are fully coherent [25]. This is true when the

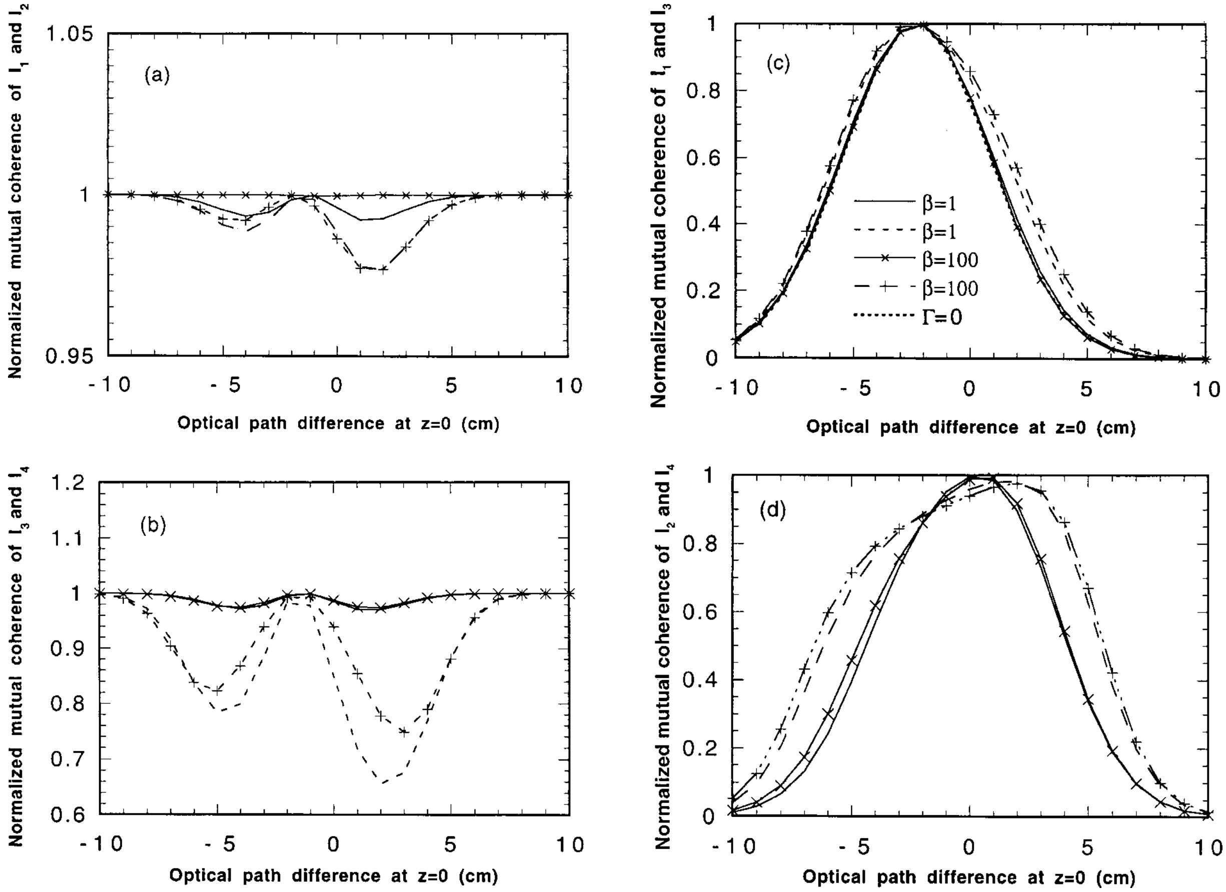

FIG. 3. Normalized mutual coherence waves as a function of the optical path difference between the signal beam and the second pump beam at position $z=0$. Solid lines are for the transmission grating dominated case (case 1), broken lines are for the reflection dominated case (case 2). The curves with (without) symbols are for $\beta=100$ $(\beta=1)$, respectively. (a) Normalized mutual coherence of the signal beam and the first pump beam at position $z=L$. In case 1, when $\beta \gg 1$, the effect of the reflection grating can be neglected. (b) Normalized mutual coherence of the PC beam and the second pump beam at position $z=0$. The presence of the reflection leads to a decrease of the mutual coherence. (c) Normalized mutual coherence of the signal beam and the second pump beam at position $z=L$. The curves for case 1 and the curve for no coupling are overlapped, which denotes that there is no contribution to the coherence of the signal beam and the second pump beam if only transmission gratings are involved. (d) Normalized mutual coherence of the PC beam and the first pump beam at position $z=0$. In case 2, reflection grating can improve the mutual coherence of the PC beam and the first pump beam substantially. The maximum shifts to a positive OPD.

OPD is very large for the general case, because there is no reflection grating recorded for a large OPD. When the OPD is small, the presence of the reflection grating decreases the normalized mutual coherence. But increasing the pump-signal ratio can increase the normalized mutual coherence. We also note that the effect is asymmetric. The reflection grating has a greater effect on the mutual coherence of A_1 and A_2 (A_3 and A_4) for a positive OPD than for a negative OPD. This is true because the energy is only coupled to one direction (i.e., the c axis of a crystal if the coupling constant is negative.)

Figures 3(c) and 3(d) show the difference between the general case and RGA. Figure 3(c) shows the coherence of A_1 and A_3 at the boundary $z=L$. The presence of wave mixing can increase the coherence. The mutual coherence of A_1 and A_3 is the smallest for any OPD if there is no coupling. In case 1, the coherence of A_1 and A_3 is nearly symmetric with respect to the crystal, while in case 2, the effect is asymmetric. This is equivalent to the RGA [26]. The presence of the reflection grating can increase the coherence of A_1 and A_3 substantially compared to case 1. It has a greater effect for a positive OPD than for a negative OPD. The mutual coherence of A_1 and A_3 can be enhanced by increasing the pump-signal beam ratio. Figure 3(d) shows the coherence of A_2 and A_4. Note that it is much different from RGA where the coherence of A_2 and A_4 at $z=0$ is an increasing function of OPD [26]. The decrease of the mutual coherence of A_2 and A_4 at $z=0$ at large OPD is due to the multiple wave coupling process. Comparing to case 1, the presence of the reflection grating can increase the mutual coherence of the PC beam and the pump beam substantially. Also, the mutual coherence of A_2 and A_4 can be increased with increasing the pump-signal beam ratio in either case.

IV. CONCLUSION

In summary, we introduced a theoretical model and studied four-wave mixing with the partially coherent wave in photorefractive materials in the general cases. The theoretical model can be applied to FWM (including FWM with the transmission grating approximation and FWM with the reflection grating approximation) and TWM with partially or fully coherent waves. Numerical results showed that the presence of reflection can increase the PC reflectivity and the coherence of the signal beam (A_1) and the second pump beam (A_3). It can also increase the mutual coherence of the PC beam and the second pump beam. However, the presence of reflection grating always leads to a drop of the mutual coherence of the PC beam and the first pump beam (A_2), and a drop of the mutual coherence of the signal beam and the second pump beam. In the case where reflection grating is dominant, the presence of reflection can increase the signal gain. While in the case where the transmission grating is dominant, it can increase the signal gain at a smaller pump-signal ratio, but decrease the signal gain at a larger pump-signal ratio.

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