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Minimization of the fluctuation in the signal beam intensity of a nonlinear optical medium with a transmission grating

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A B S T R A C T

Fluctuation in the intensity of the output signal beam of a photorefractive optical resonator can be reduced significantly by employing pump beam positive feedback. The fractional intensity transfer which is independent of time in the absence of fluctuation becomes time dependent in the presence of fluctuation of the optical wave-mixing process. The influence of various controlling parameters on the relative fluctuation of the output signal intensity has also been studied.

1. Introduction

Since the discovery of photorefractive effect [1] it is one of the most interesting subjects in the field of non-linear optics. Capability of high optical non-linearity of photorefractive effect with low power in milliwatt has attracted research interest considerably from the last four decades, both experimentally as well as theoretically [2–5]. This effect has many promising applications in real time optical signal processing, optical neutral network implementations, optical information processing systems, mass memories, optical phase conjugation, optoelectronic correlators, two-wave mixing experiments for image amplifications, etc. [4–8].

The earliest work on temporal dynamics in two-beam coupling concentrates on the transient behavior of the volume hologram build-up or decay and temporal behavior during a photorefractive process [9–18]. There are several possible sources of noise in photorefractive systems. Randomly distributed charged particles arising from the ionized dopants and defects produce inhomogeneities in the refractive index that scatter light [10]. Thermally induced fluctuations in the space-charge field can produce noise through the Pockels effect, the Kerr effect, or a combination of the two, depending on the type of crystal [11–14]. Quantum noise can also have an effect; however, it has been shown that this source is typically negligible in comparison to the other sources [11–13]. Fluctuations in the pump beam are also contributed to the signal beam noise. In addition, extraneous effects, such as random mirror vibrations and thermally induced changes in the active medium, can produce random cavity detuning and loss fluctuations [15]. All of these noise sources must be considered in a thorough examination of signal beam quality when photorefractive materials are used in resonator-based optical processing systems.

One way to determine the internal photorefractive properties of a medium is through careful analysis of its temporal behavior. One of the main differences between the photorefractive effect and other non-linear optical phenomena is that in the photorefractive effect the output usually shows a large temporal fluctuation. It is generally believed that this fluctuation is due to the presence of external noise, such as the vibration of an optical bench and the flow of environmental air. However, even when we perform the experiment in a dark room and make environmental influences such as flowing air and vibration of the optical bench as weak as possible, the fluctuation is still large indicating that the fluctuation of the output in the photorefractive effect may result from the intrinsic properties of the photorefractive effect rather than from external noise [16]. One of the problems to be solved in applications is the temporal fluctuation of the non-linear optical effect. For example, a small thermal excitation of free charge carriers and a very small temporal fluctuation of the total light intensity will result in a large temporal fluctuation of the photorefractive effect, which then induces a large fluctuation in the output signal of the photorefractive wave-mixing systems [16–19]. In order to improve the performance and application of these nonlinear optical phenomena, it is desirable to have the output signal as stable as possible.

Non-linear optical phenomena, such as second harmonic generation, sum-frequency and/or difference-frequency generation,

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stimulated Raman scattering, two-beam coupling, and degenerate four-wave mixing, etc., are related to wave mixing between the pump and the signal beams [20–24] have wide ranged applications in signal processing. One of the problems associated with the applications of these non-linear optical phenomena is the temporal fluctuation of the output signal resulting due to fluctuations of the non-linear effects. For reducing the fluctuation of the output signal beam in electrical amplifiers circuit or electrical networks, feedback circuit method is the most well known method [25]. In this method, some fraction of the output signal is feed to the input signal. After applying the feedback method the final gain of the electrical amplifier is reduced by a factor $(1-A\beta)$, where A is the gain of the amplifier without the feedback circuit and β is the gain of the feedback circuit. One can see that the relative fluctuation of the final output from the amplifier can be reduced by the same factor $(1-A\beta)$. This greatly improves the performance of the amplifier. However, the minimization of the output by use of the above feedback method makes it impractical for the non-linear optical systems, which do not have high gain.

In this communication, the fluctuation in the intensity of the output signal beam in a nonlinear optical photorefractive cavity by employing a pump beam feedback method has been studied in order to improve the performance and application of the optical wave-mixing system of non-linear optical phenomenon to have stable output i.e., without any fluctuation in the output signal. In this method, a fraction of intensity of the output pump beam is feedback to the intensity of the input pump beam by a positive feedback i.e. the feed portion from the output pump is in appropriate phase with the input pump beam and can be applicable to any physical system where the pump beam is available at the output terminal and the total energy of the intensities of the pump beam and the signal beam is conserved. The advantage of this pump beam feedback method is its simplicity and the fact that the intensity of the output signal is not reduced so that it is applicable to any optical wave-mixing systems, such as second harmonic generation, sum-frequency and/or difference-frequency generation, stimulated Raman scattering, two-beam coupling, and degenerate four-wave mixing where only a transmission grating is responsible for optical wave-mixing. Effects of various controlling parameters of non-linear optical media such as output pump phase fluctuation, decay constant of the material, intensity feedback reflectivity and crystal thickness of the material, on the relative fluctuation of the output signal intensity in a nonlinear optical medium via photorefractive two-beam coupling have also been studied in detail.

2. Theory

Let us consider a non-linear medium of thickness l placed along the z-axis with one end at $z=0$ and the other end at $z=l$. The signal and pump beams are taken to be propagating along the z-axis. Let the intensities of the signal and pump beams be I_{s0} and I_{p0} at $z=0$; I_{sl} and I_{pl} at $z=l$ in the absence of fluctuation of the wave-mixing process and I_{s0}^t and I_{p0}^t at $z=0$ and I_{sl}^t and I_{pl}^t at $z=l$ at any time t in the presence of fluctuation of the wave-mixing process.

In the absence of fluctuation of the wave-mixing process the sum of the input signal and pump intensities I_{s0} and I_{p0} decays exponentially due to material absorption and scattering as,

$$I_{sl}+I_{pl}=(I_{sl}+I_{pl})e^{-\alpha l} \tag{1}$$

i.e., the total output intensity of the signal and the pump beams is exactly equal to their total input intensity multiplied by the linear absorption factor. Where α is the decay constant and it includes the effect of the absorption and scattering both. The energy conservation [26] demands that the sum of the signal and pump beam intensities at $z=l$ in the absence and in the presence of the fluctuation of the wave-mixing process must be equal i.e.,

$$I_{sl}^t+I_{pl}^t=I_{sl}+I_{pl} \tag{2}$$

Eqs. (1) and (2) yield the following expression,

$$I_{sl}^t+I_{pl}^t=(I_{s0}+I_{p0})e^{-\alpha l} \tag{3}$$

Temporal fluctuation of the nonlinear wave-mixing process causes fluctuation of the output signal intensity. This fluctuation of the output signal intensity I_{sl}^t can be reduced by a suitable feedback.

Let the fractional energy transfer (energy transfer efficiency) from pump beam p to signal beam s be η_0 for the ideal case (without fluctuation) of wave-mixing process, i.e.,

$$\eta_0=\frac{I'_{sl}}{I_{p0}} \tag{4}$$

where I'_{sl} is the difference of the signal beam intensities with and without wave-mixing process at $z=l$, i.e.,

$$I'_{sl}=I_{sl}-I_{s0}e^{-\alpha l} \tag{5}$$

Conservation of energy leads to the following relation,

$$I'_{sl}+I_{pl}=I_{p0}e^{-\alpha l} \tag{6}$$

The fractional intensity transfer η which is independent of time in the absence of fluctuation ($\eta=\eta_0$), becomes time dependent in the presence of fluctuation of the wave-mixing process i.e.,

$$\eta=\eta_0+\eta_t \tag{7}$$

where η_t is fluctuating part of the fractional intensity transfer and is very small as compared to η_0. Now the energy transfer from the pump beam to the signal beam can be written as,

$$\eta I_{s0}=I'_{sl}+\varepsilon_t \tag{8}$$

where ε_t is fluctuating part of the transferred intensity to the output signal. The value of ε_t is negligibly small compared to I'_{sl}. Eqs. (4) and (8) lead to,

$$\varepsilon_t=\eta_t I_{p0} \tag{9}$$

We take the input pumped intensity as

$$I_{p0}^t=I_{p0}-\sigma_t \tag{10}$$

To make

$$\eta(I_{p0}-\sigma_t)=I'_{sl}$$

$$\sigma_t\approx\frac{I_{p0}}{I'_{sl}}\varepsilon_t \tag{11}$$

Now energy conservation leads

Fluctuating analogue of Eq. (6) can be obtained by replacing I_{pl} by I_{pl}^t and I_{p0} by I_{p0}^t in Eq. (6) and using Eq. (10) as,

$$I'_{sl}+I_{pl}^t=I_{p0}e^{-\alpha l}-\sigma_t e^{-\alpha l} \tag{12}$$

Eqs. (6) and (12) yield the following expression

$$I_{pl}^t=I_{pl}-\sigma_t e^{-\alpha l} \tag{13}$$

In order to achieve condition required by Eq. (10), a fraction of the output pump wave amplitude a_{pl}^t can be fed back to the input pump wave amplitude a_{p0}. If the effective coefficient of reflection of all the feedback mirrors is r, the pump wave amplitude at the input surface $z=0$ is given by,

$$a_{p0}^t=a_{in}+re^{j\delta}a_{pl}^{t-\Delta t} \tag{14}$$

2.1. Analysis of fluctuation in the absence of phase coupling between the mixing waves

First, we consider the case in which there is no phase coupling between the mixing waves. In other words, the phase of the mixing waves is not influenced by the wave-mixing process, such as in photorefractive wave-mixing with a real coupling Coefficient (i.e., no applied electric field existing in a photorefractive medium with a diffusion of charge carriers), and in second harmonic generation with perfect phase matching. For this case, the fluctuation of the wave-mixing process only induces fluctuations in the intensity of the mixing waves, whereas the phase of the mixing waves is constant in time. For constructive interference to take place between the input pump wave and the feedback fraction of the output pump wave δ must be an integral multiple of 2π. Assuming Δt to be negligibly small ($\Delta t\to 0$) compared to the response time $e(\tau)$ of the nonlinear medium the Eq. (14) assumes the form,

$$a_{p0}^t = a_{in} + re^{2ni\pi}a_{pl}^t \quad n = 0,\ 1,\ 2,\ 3,\ \ldots . \tag{15}$$

Since$a_{pl}^t=\sqrt{I_{pl}^t}$, Eqs. (15) and (13) give,

$$a_{pl}^t = a_{in} + \left(\sqrt{I_{pl} - \sigma_t e^{-\alpha l}}\right)e^{j2n\pi} \tag{16}$$

Taking positive and real a_{in} and squaring Eq. (16) one obtains

$$(a_{pl}^t)^2 = a_{in}^2 + r^2(I_{pl} - \sigma_t e^{-\alpha l}) + 2a_{in}r(\sqrt{I_{pl} - \sigma_t e^{-\alpha l}})$$

or

$$I_{p0}^t = (a_{in} + r\sqrt{I_{pl}})^2 - 2a_{in}r(\sqrt{I_{pl}} - \sqrt{I_{pl} - \sigma_t e^{-\alpha l}}) - r^2\sigma_t e^{-\alpha l} \tag{17}$$

Taking

$$I_{p0} = (a_{in} + r\sqrt{I_{pl}})^2 \tag{18}$$

From Eqs. (10) and (17) we get,

$$I_{p0}^t = (a_{in} + r\sqrt{I_{pl}})^2 - \sigma_t \tag{19}$$

Comparing Eqs. (17) and (19) we get

$$(1 - r^2 e^{-\alpha l})\sigma_t = 2a_{in}r(\sqrt{I_{pl}} - \sqrt{I_{pl} - \sigma_t e^{-\alpha l}}) \tag{20}$$

From Eq. (18) we have

$$a_{in} = \sqrt{I_{p0}} - r\sqrt{I_{pl}} \tag{21}$$

Putting the value of a_{in} from Eq. (21) into Eq. (20) gives,

$$(1 - r^2 e^{-\alpha l})\sigma_t = 2\sqrt{I_{pl}}(r\sqrt{I_{p0}} - r^2\sqrt{I_{pl}})\left(1 - \sqrt{1 - e^{-\alpha l}\left(\frac{\sigma_t}{I_{pl}}\right)}\right) \tag{22}$$

Expanding the second term of the second bracket of the RHS of Eq. (22) and keeping terms up to the first order only one obtains,

$$r^2 = R = \frac{I_{pl}}{I_{p0}}e^{2\alpha l} \tag{23}$$

The feedback reflectivity R is independent of σ_t it means that if we take R as Eq. (23) we can reduce the fluctuation of the output signal intensity greatly, the output signal intensity fluctuation with an order of magnitude less than that without the feedback. For a feedback reflectivity smaller than that given in Eq. (23), the feedback pump intensity is not large enough to compensate for the fluctuation of the signal, but it can still reduce the fluctuation of the signal. On then other hand for the feedback reflectivity slightly larger than that given in Eq. (23) the feedback gives small extra feedback pump intensity besides that compensate for the fluctuation of the signal which slightly reduces the reduction efficiency.

Similarly, assume that that there are n pump beams I_{pi}, where I=1,2,3, …, n and one signal beam I_S, which satisfy the following energy conservation

$$I_{sl}^t + \sum_{i=1}^{n} I_{pil}^t = \left[I_{s0} + \sum_{i=1}^{n} I_{pi0}\right]e^{-\alpha l} \tag{24}$$

Similarly, the sum-frequency or difference-frequency generation assumed in case of two pump beams. We can show that in order to reduce the temporal fluctuation of the output signal to the least level R_i can take the following form

$$R_i = \frac{I_{pil}}{I_{pi0}}e^{2\alpha l} \tag{25}$$

That means that every output pump beam is feedback to the input in the same way as in the case of one pump beam. We analyze the reduction efficiency by using this method (taking feedback reflectivity as Eq. (23)). For this purpose, substituting Eq. (23) into Eq. (17) making use of Eq. (18), keeping terms up to the second order of $\sigma_t e^{-\alpha l}/I_{pl}$ we get

$$I_{p0}^t = I_{p0} - \sigma_t - \frac{1}{4}\frac{I_{sl}}{I_{pl}I_{p0}}\sigma_t^2 \tag{26}$$

the output signal intensity is

$$I'^t_{sl} = \eta\, I_{p0}^t = \eta\left(I_{p0} - \sigma_t - \frac{1}{4}\frac{I_{sl}}{I_{pl}I_{p0}}\sigma_t^2\right)$$

after solving the equation we get

$$I'^t_{sl} = I'_{sl} - \eta_t\sigma_t - \frac{(I'^t_{sl} + \varepsilon_t)I'_{sl}}{4I_{pl}I_{p0}^2}\sigma_t \tag{27}$$

neglecting the third order term, we rewrite Eq. (27) as

$$I'^t_{sl} \approx I'_{sl} - \left(\frac{1}{I'_{sl}} + \frac{1}{4I_{pl}}\right)\varepsilon_t^2 \tag{28}$$

Comparing Eqs. (8) and (28) we see that the fluctuation is reduced from ε_t (without feedback) to $((1/I'_{sl})+(1/4I_{pl}))\varepsilon_t^2$ (with feedback).

In practice, because of the imprecise adjustment there exist more or less a small phase deviation ϑ of $e^{i\delta}a_{sl}^t$ from the input phase of a_{in}, i.e. the phase of $e^{i\delta}a_{sl}^t$, and that of a_{in} may not be exactly in phase. Therefore, it is interesting to discuss the effect of a small phase deviation ϑ on the reduction efficiency. The feedback reflectivity is still taken as $R=I_{pl}/I_{p0}e^{2\alpha l}$. Eq. (16) now becomes

$$a_{p0}^t = a_{in} + \sqrt{R}(\sqrt{I_{pl} - \sigma_t e^{-\alpha l}})e^{j(2n\pi + \vartheta)} \tag{29}$$

Where the input pump amplitude is taken as

$$a_{in} = a_{p0} - \sqrt{R}\sqrt{I_{pl}}e^{j(2n\pi + \vartheta)} \tag{30}$$

Here as before, a_{in} is assumed to be real and positive. Assuming$a_{p0}=\sqrt{I_{p0}}e^{i\vartheta}$, we obtain

$$a_{in} = \sqrt{I_{p0}}\cos\theta - \frac{I_{pl}}{\sqrt{I_{p0}}}e^{\alpha l}\cos\vartheta \tag{31a}$$

$$\sin\theta = \frac{I_{pl}}{I_{p0}}e^{\alpha l}\sin\vartheta \tag{31b}$$

Substituting Eqs. (31a) and (31b) and R in Eq. (29) and keeping terms up to the second order of $\sigma_t e^{-\alpha l}/I_p$, we obtain

$$I_{p0}^t = I_{p0} - \left(\cos\theta\cos\vartheta + \frac{I_{pl}}{I_{p0}}e^{\alpha l}\sin^2\vartheta\right)\sigma_t + \left(\frac{\cos^2\vartheta}{4I_{p0}} - \frac{\cos\theta\cos\vartheta}{4I_{pl}}e^{-\alpha l}\right)\sigma_t^2 \tag{32}$$

The output signal intensity reads as

$$I'^{t}_{sl} = I'_{sl} + \left\{ \frac{1}{2}\left(1 - \frac{I_{pl}}{I_{p0}} e^{\alpha l}\right)^2 \sin^2 \vartheta \right\} \varepsilon_t - \left(\frac{1}{I'_{sl}} + \frac{1}{4I_{pl}} \right) \varepsilon_t^2 + a \sin^2 \vartheta \varepsilon_t^2 \tag{33}$$

$$I'^{t}_{sl} = I'_{sl} + \frac{1}{2}\left(1 - \frac{I_{pl}}{I_{p0}} e^{\alpha l}\right)^2 \vartheta^2 \varepsilon_t - \left(\frac{1}{I'_{sl}} + \frac{1}{4I_{pl}} \right) \varepsilon_t^2 + a \vartheta^2 \varepsilon_t \tag{34}$$

where

$$a = \frac{1}{2I'_{sl}} \left(1 - \frac{I_{pl}}{I_{pl}} e^{\alpha l}\right)^2 - \left(\frac{1}{4I'_{sl}} + \frac{I_{p0} e^{-\alpha l}}{8I'_{sl} I_{pl}} + \frac{I_{p0} e^{\alpha l}}{8I'_{sl} I_{p0}} \right) \tag{35}$$

Eqs. (33) and (34) reduces to Eq. (28) in the limit $\vartheta \to 0$. Eq. (33) and (34) means that, in the presence of a small phase deviation ϑ of $e^{i\delta} a^t_{pl}$ from the input phase of a_{in}, the fluctuation of the output signal intensity (in the approximation of the first order of magnitude) can be reduced from ε_t (without feedback) to

$$\left\{ \frac{1}{2}\left(1 - \frac{I_{pl}}{I_{pl}} e^{\alpha l}\right)^2 \vartheta^2 \right\} \varepsilon_t$$

(with feedback). Noting $I_{pl}/I_{pl} e^{\alpha l} < 1$, term

$$\frac{1}{2}\left(1 - \frac{I_{pl}}{I_{p0}} e^{\alpha l}\right)^2 \vartheta^2$$

is a very small value for a small phase deviation ϑ.

2.2. Analysis of fluctuation in the presence of phase coupling between the mixing waves

We consider the case in which there exist phase coupling between the mixing waves. In other words, the phase of the mixing waves is influenced by the wave-mixing process, such as in photorefractive wave-mixing with a complex coupling coefficient and in second harmonic generation with phase mismatching. For this case, the fluctuation of the wave-mixing process not only induces the fluctuation of the intensity of the wave mixing but also induces the fluctuation of the phase of the mixing waves. Thus the phase of the pump and signal beams at output surface fluctuates in time around a mean value. Now adjusting the cavity phase δ to make the mean phase of $e^{i\delta} a^t_{pl}$ and that of a_{in} in phase, from Eq. (13), we rewrite Eq. (14) in the limit of $\Delta t \to 0$ as

$$a^t_{p0} = a_{in} + \sqrt{R}\left(\sqrt{I_{pl} - \sigma_t e^{-\alpha l}}\right) e^{j(2n\pi + \phi_t)} \tag{36}$$

where n=0,1,2,3, …, ϕ_t is the small fluctuating phase of a^t_{pl} relative to its mean phase. Here, we also assume a_{in} to be real and positive. As in case I, we take the feedback reflectivity as $R = I_{pl}/I_{p0} e^{2\alpha l}$ and the input pump amplitude as $a_{in} = \sqrt{I_{p0}} - \sqrt{R}\sqrt{I_{pl}}$ (the case without the fluctuation of the intensity and the phase). Substituting a_{in} and R into Eq. (36), and keeping terms up to the first order of $\sigma_t e^{-\alpha l}/I_{pl}$,

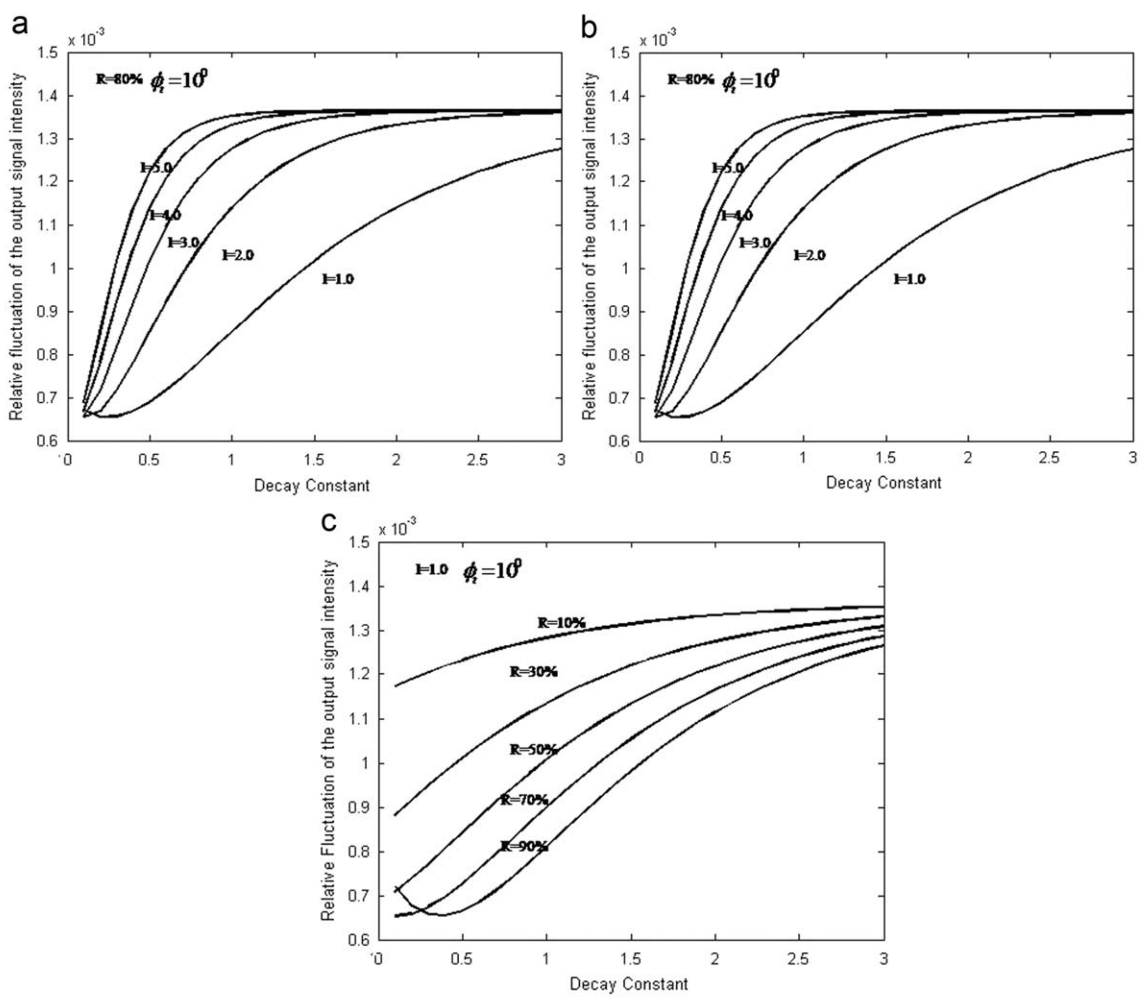

Fig. 1. Relative fluctuation of the output signal beam intensity '$\Delta I'_{sl}/I'_{sl}$' with decay constant 'α' for different values of (a) ϕ_t (fixed R and l); (b) l (fixed ϕ_t and R); and (c) R (fixed ϕ_t and l).

we obtain

$$I_{p0}^{t} = I_{p0} - \sigma_t - 4I_{pl}e^{\alpha l}\left(1 - \frac{I_{pl}}{I_{p0}}e^{\alpha l}\right)\sin^2\frac{\phi_t}{2} + 2\left(1 - \frac{I_{pl}}{I_{p0}}e^{\alpha l}\right)\sin^2\frac{\phi_t}{2}\sigma_t \quad (37)$$

The output signal intensity reads

$$I'^{t}_{sl} = I'_{sl}\left[1 - 4\frac{I_{pl}}{I_{p0}}e^{\alpha l}\left(1 - \frac{I_{pl}}{I_{p0}}e^{\alpha l}\right)\sin^2\frac{\phi_t}{2}\right] + 2\left(1 - \frac{I_{pl}}{I_{p0}}e^{\alpha l}\right)\left(1 - 2\frac{I_{pl}}{I_{p0}}e^{\alpha l}\right)\sin^2\frac{\phi_t}{2}\varepsilon_t \quad (38)$$

or,

$$I'^{t}_{sl} = I'_{sl}\left[1 - \frac{I_{pl}}{I_{p0}}e^{\alpha l}\left(1 - \frac{I_{pl}}{I_{p0}}e^{\alpha l}\right)\phi_t^2\right] + \left(1 - \frac{I_{pl}}{I_{p0}}e^{\alpha l}\right)\left(1 - 2\frac{I_{pl}}{I_{p0}}e^{\alpha L}\right)\frac{\phi_t^2}{2}\varepsilon_t \quad (39)$$

It is noted that the fluctuation of the signal intensity is mainly dependent on the term

$$\frac{I_{pl}}{I_{p0}}e^{\alpha l}\left(1 - \frac{I_{pl}}{I_{p0}}e^{\alpha l}\right)\phi_t^2 \quad (40)$$

Noting $0 < (I_{pl}/I_{p0}e^{\alpha l}) < 1$, we obtain that the maximum of

$$\frac{I_{pl}}{I_{p0}}e^{\alpha l}\left(1 - \frac{I_{pl}}{I_{p0}}e^{\alpha l}\right)\phi_t^2$$

is $0.25\phi_t^2\ at (I_{pl}/I_{p0})e^{\alpha l} = 0.5$.The maximum value $0.25\phi_t^2$is a very small value for a small fluctuation ϕ_t. From Eq. (39) it is to be noted that for a small fluctuation ϕ_t, the fluctuation of the output signal intensity is very small. Therefore, the relative fluctuation of the output signal intensity in the optical photorefractive wave mixing system is given by relation as,

$$\frac{\Delta I'_{sl}}{I'_{sl}} = \frac{I_{pl}}{I_{p0}}e^{\alpha l}\left(1 - \frac{I_{pl}}{I_{p0}}e^{\alpha l}\right)\frac{\phi_T^2}{2} \quad (41)$$

From Eq. (23) into Eq. (41), we get

$$\frac{\Delta I'_{sl}}{I'_{sl}} = Re^{-\alpha l}(1 - Re^{-\alpha l})\frac{\phi_t^2}{2} \quad (42)$$

Eq. (42) represents the fluctuation in the intensity of the output signal beam relative to its mean intensity in the nonlinear optical wave-mixing systems.

3. Results and discussion

The relative fluctuation in the intensity of the output signal beam ($\Delta I'_{sl}/I'_{sl}$) depends on the phase fluctuation in the output pump beam (ϕ_t), crystal thickness of the material (l), decay constant (α) due to the effect of the absorption and scattering and

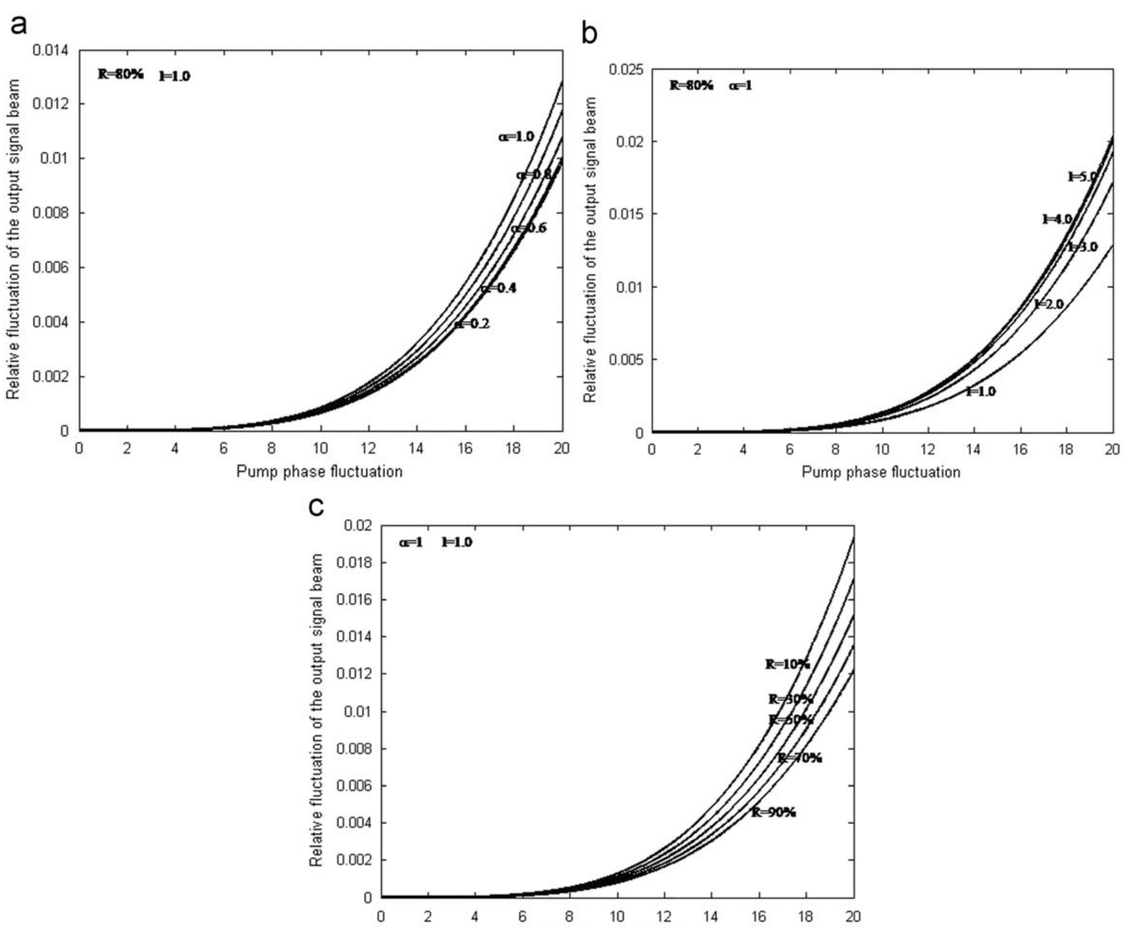

Fig. 2. Relative fluctuation of the output signal beam intensity '$\Delta I'_{sl}/I'_{sl}$' with phase fluctuation in the output pump beam 'ϕ_t' for different values of (a) α (fixed R and l); (b) l (fixed α and R); and (c) R (fixed α and l).

feedback reflectivity $R=I_{pl}/I_{p0}e^{2\alpha l}$ of the mirrors (Eq. (42)). The variations of relative fluctuation of the output signal intensity ($\Delta I'_{sl}/I'_{sl}$) with α for different values of ϕ_t (fixed R=80% and l=1), l (fixed ϕ_t=10° and R=80%) and R (fixed ϕ_t=10°and l=1) are shown in Figs. 1(a)–(c) respectively. It can be seen from Fig. 1(a) that for R=80% and l=1, the relative fluctuation in the intensity of the output signal beam initially decreases with decay constant up to the certain value of decay constant ($\alpha<0.3$) and afterwards it increases with increasing value of decaying constant which arises due to absorption and scattering of the light beam. However, it can be seen that the relative fluctuation in the intensity of the output signal beam of the non-linear photorefractive crystal with respect to its mean intensity can be suppressed to larger extent by decreasing the fluctuation in the phase of the output pump beam to the lowest order. From Fig. 1(b) it is obvious that the relative fluctuation of the output signal beam intensity increases rapidly with increasing value of decay constant of the material and reaches to a maximum value at a certain value of decay constant afterwards it becomes saturated. However, it is also to be noted that for higher values of l, the relative fluctuation output signal beam intensity increases sharply with its maximum value at a very small value of decay constant. Fig. 1(c) shows that with increasing value of decay constant of the material, the relative fluctuation of the output signal beam intensity increases and reaches a maximum value at the certain value of decay constant ($\alpha<3$) afterwards it becomes saturated. From Fig. 1(c) one may conclude that the fluctuation in the intensity of the output signal beam at the output surface of the nonlinear optical cavity in the photorefractive materials can be minimized greatly to quite low level by having higher value of intensity feedback reflectivity of the cavity mirrors which could exist at a very low value of decay constant.

Figs. 2(a)–(c) respectively show the variation of relative fluctuation of the output signal beam intensity ($\Delta I'_{sl}/I'_{sl}$) with ϕ_t for the different values of α (fixed R=80% and l=1), l (fixed α=1 and R=80%) and R (fixed α=1 and l=1). From Fig. 2(a) it is obvious that for a given value of decay constant (α), the fluctuation in intensity of the output signal beam increases rapidly with increasing value of phase fluctuation in the output pump beam (ϕ_t). However, the relative fluctuation in the intensity of the output signal beam of the wave-mixing system can be reduced to the minimum level by decreasing the value of decay constant to the lowest possible level. It is also to be noted that for the different values of R, any two $\Delta I'_{sl}/I'_{sl}$ vs. ϕ_t curves do not coincide (Fig. 2(c)) whereas, $\Delta I'_{sl}/I'_{sl}$ vs. ϕ_t curves with different values of α coincide for α=0.2 and α=0.4 (Fig. 2(a)). Thus one can conclude that for the value of decay constant α=0.2 and α=0.4, the fluctuations in the intensity of the output signal beam is not affected by the material absorption and scattering of the light beam. Similar variations of $\Delta I'_{sl}/I'_{sl}$ vs. ϕ_t can be seen from Fig. 2(c). In this case also, as the intensity feedback reflectivity (R) of the cavity mirrors increases, the fluctuation in the intensity of the

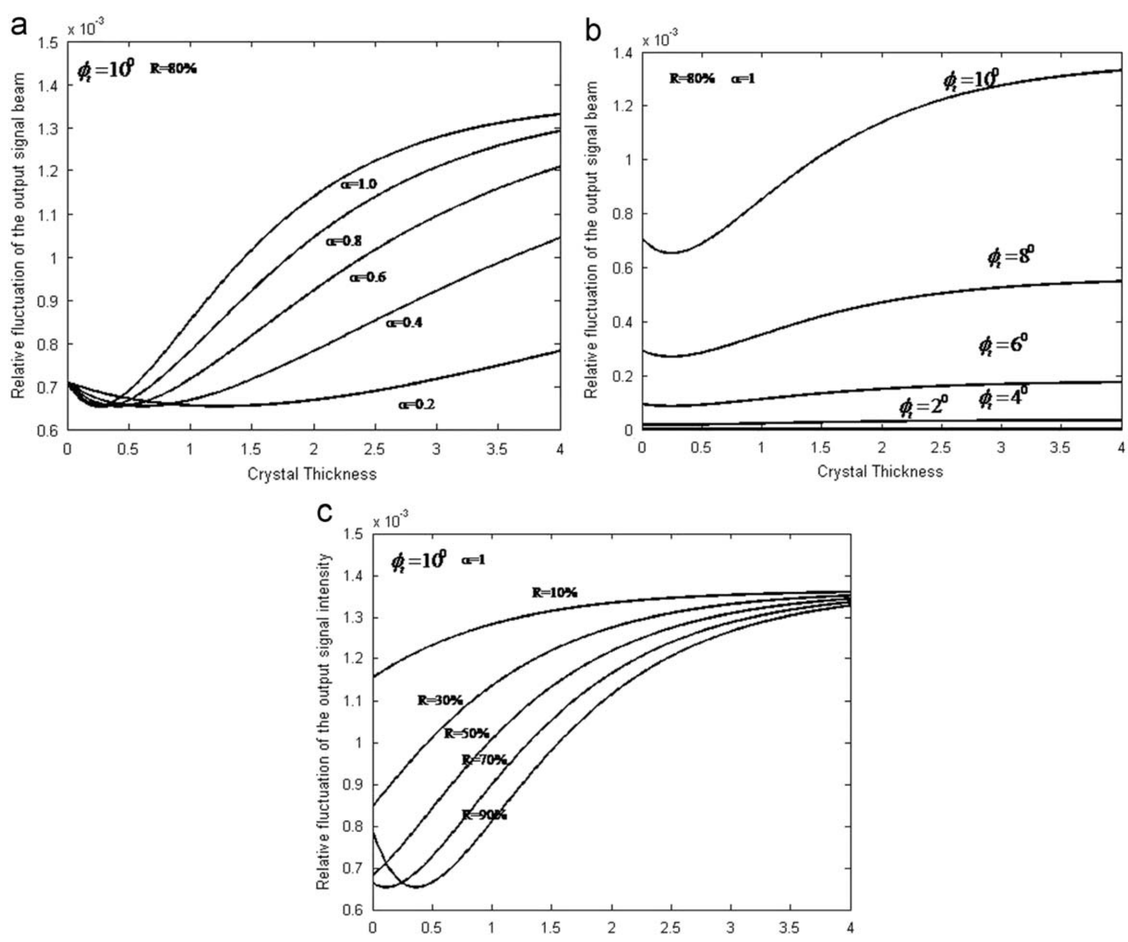

Fig. 3. Relative fluctuation of the output signal beam intensity '$\Delta I'_{sl}/I'_{sl}$' with the crystal thickness of the material 'l' for different values of (a) α (fixed R andϕ_t); (b) ϕ_t (fixed α and R); and (c) R (fixed α and ϕ_t).

output signal beam decreases from $\sim$0.019 for R=10% to $\sim$0.012 for R=90%. This means that the fluctuation in the intensity of the output signal beam relative to its mean intensity can be greatly suppressed by increasing the value of intensity feedback reflectivity (R>90%) of the cavity mirrors.

Figs. 3(a)–(c) respectively present the variation of relative fluctuation in the intensity of the output signal beam ($\Delta I'_{sl}/I'_{sl}$) with l for the different values of α (fixed R=80% and ϕ_t=10°), ϕ_t (fixed α=1 and R=80%) and R (fixed α=1 and ϕ_t=10°). It can be seen from Fig. 3(a) that the fluctuation in the intensity of the output signal beam relative to its mean intensity increases with the increasing value of the crystal thickness. For higher values ofα, the relative fluctuation in the intensity of the output signal beam increases more rapidly compared to the lower value ofα. It is evident from Fig. 3(b) that the relative fluctuation of the output signal beam intensity ($\Delta I'_{sl}/I'_{sl}$) increases with the increasing value of the crystal thickness and the fluctuation in the intensity of the output signal beam is minimum for a very small phase fluctuation in the output pump beam. From Fig. 3(c) it is obvious that with the increasing value of the crystal thickness, the relative fluctuation of the output signal beam intensity increases.

Figs. 4(a)–(c) respectively depict the variation of relative fluctuation in the intensity of the output signal beam ($\Delta I'_{sl}/I'_{sl}$) with R for the different values of α (fixed l=1 and ϕ_t=10°), ϕ_t (fixed α=1 and ϕ_t=10°) and l (fixed α=1 and l=1). It can be seen from Fig. 4(a) that for a given value of decay constant (α), the relative fluctuation in the intensity of the output signal beam with respect to its mean intensity increases exponentially with increasing the value of intensity feedback reflectivity. It could also be conclude from Fig. 4(a) that the relative fluctuation in the intensity of the output signal could be suppressed at the output terminal by taking the higher values of the decay constant (α>1) and feedback reflectivity ($R>90\%$). Fig. 4(b) shows that for a given value of phase fluctuation in the output pump beam at the output surface of the photorefractive medium, the relative fluctuation in the intensity of the output signal beam at the output surface initially decreases with the increasing the value of R and reaches to the minimum value at a certain value of intensity feedback reflectivity and afterwards it increases rapidly with R. For a given value of R, the relative fluctuation of the output signal beam intensity is found to be lowest for very small fluctuation in the phase of the output pump beam. This means that the temporal fluctuation of the output signal beam intensity relative to its mean intensity can be reduced appreciably at the optimum value of feedback reflectivity which greatly improves the performance and application of the wave-mixing system. From Fig. 4(c) it is clear that the fluctuation in the intensity of the output signal beam decreases initially with R and reaches to a minimum value at a certain value of R and afterwards it increases very rapidly with R.

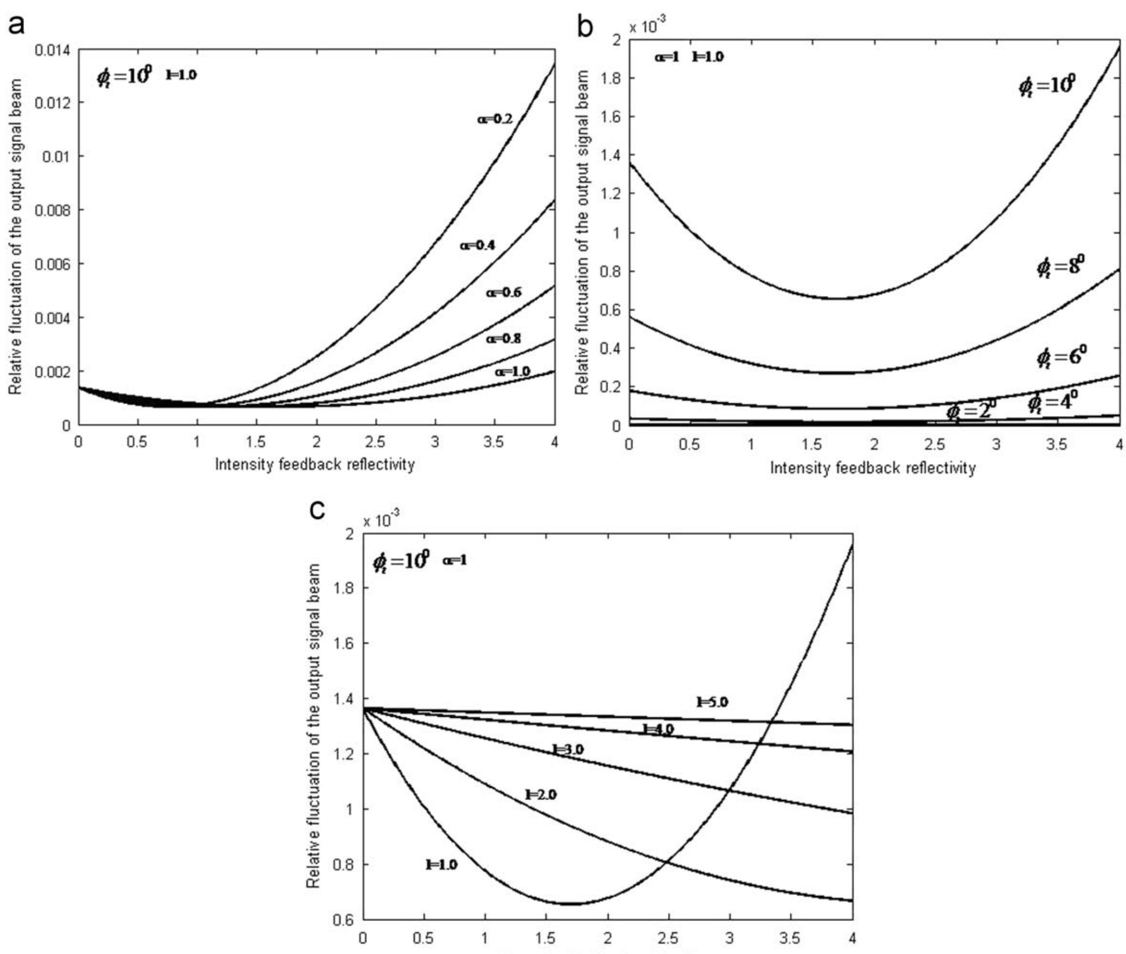

Fig. 4. Relative fluctuation of the output signal beam intensity '$\Delta I'_{sl}/I'_{sl}$' with the intensity feedback reflectivity 'R' of the cavity mirrors for different values of (a) α (fixed l andϕ_t); (b) ϕ_t (fixed α and l); and (c) l (fixed α and ϕ_t).

4. Conclusion

Minimization of fluctuation in the intensity of the output signal beam of the non-linear optical wave-mixing system formed by photorefractive materials by employing pump beam feedback method via the positive feedback of the output pump to the input pump is possible. This method could be applicable to any type of a systems, such as second harmonic generation, sum-frequency and/or difference-frequency generation, stimulated Raman scattering, two-beam coupling, and degenerate four-wave mixing where only a transmission grating is responsible for the optical wave-mixing system. It has been found that in the optical wave-mixing system with a transmission grating, the total energy of the pump and the signal beam is conserved. Using such a method, the temporal fluctuation in the intensity of the signal beam at the output surface of the non-linear cavity can be significantly reduced without reducing its mean intensity by use of positive feedback of a fraction of the intensity of the output pump beam to the intensity of the input pump beam. The advantage of this pump beam feedback method is its simplicity and the fact that the intensity of the output signal is not reduced due to the positive feedback. Moreover, smaller input pump intensity is needed as compared to a system without feedback. The curves $\Delta I'_{sl}/I'_{sl}$ vs. R for the different values of ϕ_t suggest that the relative fluctuation in the intensity of the output signal beam decreases with increasing value of the intensity feedback reflectivity. Decrease in fluctuation of the output signal intensity is small for very small fluctuation in the phase of the output pump beam. This means that the temporal fluctuation of the output signal intensity can be reduced to a minimum value at the optimum value of feedback reflectivity which greatly improves the performance and application of the wave-mixing system. It is also found from the curves $\Delta I'_{sl}/I'_{sl}$ vs. α for the different values of ϕ_t that for a given value of phase fluctuation of output pump beam, the relative fluctuation in the intensity of the output signal beam of the non-linear optical wave-mixing system can be minimized to a minimum level by decreasing the value of decay constant to the lowest possible order.

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