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ORIGINAL PAPER

Improvement of oscillation characteristics of ring oscillator through photoconductivity and dielectric constant of photorefractive materials

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Abstract: The intensity of oscillation and the oscillation frequency shift are two most important parameters that characterize the performance of a photorefractive ring oscillator. In this paper, the effect of photoconductivity and dielectric constant of photorefractive (PR) materials on these parameters has been studied in case of non-degenerate two-wave mixing in PR materials. It has been found that for a given value of photoconductivity of PR material, the highly reflecting ($R > 90\%$) cavity mirrors are much effective parameter as compared to the other parameters (frequency detuning, absorption strength, energy beam coupling strength and dielectric constant) for the enhancement of the intensity of oscillation in the oscillator. Also, the magnitude of oscillation frequency of the photorefractive ring oscillator (PRO) can be increased by inserting PR crystal of lower dielectric constant ($\varepsilon < 7.0$), higher photoconductivity ($\sigma_p > 500\,\text{pS/cm}$) and highly reflectivity ($R > 90\%$) cavity mirrors provided that the cavity-length detuning $\left(\frac{\Delta\Gamma}{\pi} > 1.0\right)$ of the oscillator is higher. This means that the intensity and frequency of the PRO could be controlled by the dielectric constant and photoconductivity of a PR crystal which would greatly improve performance of a PRO and their applications based on these photorefractive ring oscillators such as wave front color conversion, optical limiting, optical computing and beam cleanup.

Keywords: Ring oscillator; Photoconductivity; Dielectric constant of the photorefractive materials

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1. Introduction

Photorefractive effects have been extensively studied during the last decades because of their strength and diversity and also because of a large application potential [1]. These effects are present in many materials, including ferroelectric, semi-conductive crystals and polymers [2–5]. Photorefractive media provide a promising candidate for information systems because of their unique properties, such as low intensity operation, massive storage capacity, directional energy transfer, real-time response and large dynamic range [1–7]. These features make them attractive materials for fiber optic devices such as modulators, switches, dispersion compensators, filters, photorefractive oscillators and wavelength division multiplexers/demultiplexers [1–25].

Photorefractive ring oscillator (PRO) containing photorefractive crystals has proven their utility in the construction and operation of various photorefractive circuits [12–30]. Two interconnected rings with two-wave mixing crystals have been used to display an optical analog of flip-flop circuit [1, 30]. A four-wave mixing crystal can be considered as an eight-pin optical processor [1, 30]. Far-reaching potential applications for photorefractive ring oscillators are thus opening up in the field of optical computing [12–18]. Thus, in order to optimize these applications and from a theoretical point of view, a better understanding of the operation and properties of photorefractive oscillators is needed.

In this work, the influence of photoconductivity and dielectric constant of photorefractive material on the intensity of oscillation and oscillation frequency shift of a PRO has been analyzed in case of non-degenerate two-wave mixing. In the earlier published literature, the effects of photoconductivity and dielectric constant of photorefractive materials on the performance of a PRO have not been explored in details. In this paper, the above effects have been investigated thoroughly.

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2. Theory

2.1. Photorefractive ring oscillator

The schematic diagram of a photorefractive ring oscillator (PRO) is shown in Fig. 1. This ring oscillator is formed by three perfectly reflecting plane mirrors: M_1, M_2 and M_3. In this geometry, a photorefractive material in a crystal form is placed inside a ring cavity and pumped by external laser beam.

Fanning of the incident beam (i.e., scattered light) inside the photorefractive (PR) crystal takes place [2, 12, 25]. Some of fanned light is directed around loop to reenter the PR crystal via cavity mirrors. Oscillation starts from this scattered light, and if the PR crystal is placed inside a PRO, scattered light is reflected by the cavity mirrors back into the crystal and then amplified through two-wave mixing [2, 12, 19, 25]. In a PRO configuration, light propagation inside a oscillator should be two-wave mixing beam. This two-wave mixing beam should be directional and directionality of a beam is determined by the crystal's symmetry, alignment, and the charge transport properties of the crystal [2, 25]. As a results of which, the light moving in the clock wise sense and is amplified while the light moving in the anti-clock-wise sense is not amplified due to loss and vice-versa. If the two-beam coupling gain is above threshold, the oscillating beam (routed by the back into the crystal) experiences subsequent interactions with the pump beam and gets amplified on each successful round-trip [12, 19]. The oscillation beam accumulates energy from successive two-beam coupling amplification on each round-trip through the PR material until saturation sets in but losses energy from absorption and other losses such as Fresnel reflections from the crystal and imperfect mirrors [2, 12]. The oscillation beam builds up provided that the coupling efficiency exceeds the combined absorption and oscillator losses. Such a PRO has the capability of providing large amplification of weak signals and is very sensitive to minute changes in its length [2, 12, 25].

2.2. Formulation of problem

2.2.1. Frequency of oscillation and intensity of oscillating beam

The oscillation inside a PRO starts from the noise generated by scattering and quantum fluctuations [1, 2, 25, 28–30]. In a PR crystal, the scattering dominates the noise contribution. Initially, there could be a little amount of light scattered along the direction of a PRO. The two-wave mixing process in the PR crystal amplifies this scattered light having frequencies differing from the frequency of the pump beam by $\Omega(\leq 30\,\mathrm{Hz})$. Any scattered light propagating in the opposite direction should experience loss and, therefore, will not get amplified as observed in previous experiments [12–18] on a PRO. For the two-wave mixing gain above a threshold value, the resonating beam grows from the amplification of the fanned light [2]. Typical oscillator conditions require that the optical path length inside the oscillator must be equal to an integral multiple of the wavelength of the pump beam [25]. The buildup of oscillation intensity leads to a saturation of the

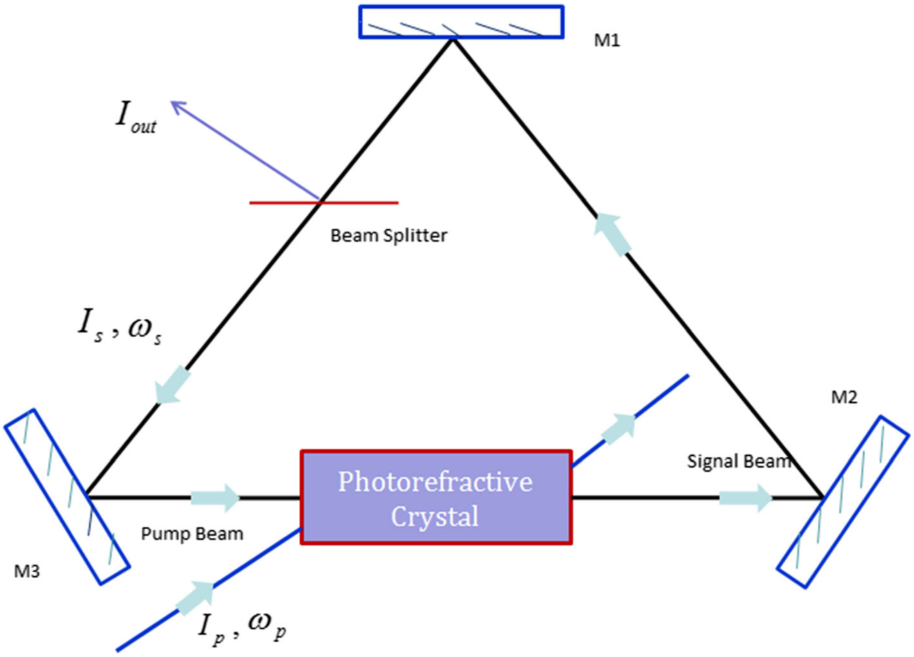

Fig. 1 Schematic diagram of a photorefractive ring oscillator (PRO)

gain [2, 25, 28, 29]. For the steady-state oscillations, after each round-trip, the phase and the intensity of the electric field of the signal beam must reproduce. Therefore, the oscillations are sustained for the conditions [1, 25, 27–30],

$$gR = 1 \tag{1}$$

$$\Delta\psi_c + \int k\mathrm{d}s = 2N\pi \tag{2}$$

In Eq. (1), the parameter R is the product of the reflectivities of the all mirrors M_1, M_2 and M_3, and g is the two-wave mixing gain inside a PRO and is given by [1, 2, 25]

$$g = \frac{(1+m)\exp(-\alpha l)}{1+m\exp(-\gamma l)} \tag{3}$$

where l is the crystal thickness of the photorefractive material, α is the effective absorption coefficient of PR material that includes combined losses from the crystal, absorption, mirror and Fresnel reflection losses [1, 25, 27, 30], and m is the input intensity ratio given by:

$$m = \frac{I_\mathrm{p}(0)}{I_\mathrm{s}(0)} \tag{4}$$

where $I_\mathrm{p}(0)$ and $I_\mathrm{s}(0)$ are the intensities of the pump beam and signal beam at the center of the left crystal plane $z = 0$, and γ is the nonlinear two-beam energy coupling constant inside a PR material and can be written as [1, 19, 27, 30]

$$\gamma = \frac{\gamma_0}{1+(\Omega\tau)^2} \tag{5}$$

where $\Omega(=\omega_\mathrm{p}-\omega_\mathrm{s})$ is the frequency detuning (oscillation frequency shift) of a PRO, ω_p and ω_s are the angular frequencies of the pump and signal beam, respectively, and τ is the response time of the photorefractive medium which is inversely proportional to photoconductivity (σ_p) as given by the relation [1, 19, 27, 30]

$$\tau = \frac{\varepsilon\varepsilon_0}{\sigma_\mathrm{p}} \tag{6}$$

where ε_0 and ε are the dielectric constant in vacuum and the relative dielectric constant of PR material, and γ_0 is the coupling constant for the case of degenerate two-wave mixing (i.e., $\Omega = \omega_\mathrm{p}-\omega_\mathrm{s} = 0$) and is given by the expression:

$$\gamma_0 = \frac{4\pi\,\Delta n_\mathrm{s}}{\lambda\cos\theta} \tag{7}$$

where Δn_s is the saturation value of the photoinduced index change, λ is the wavelength of the laser beam, and θ is the half the angle between the beams inside the photorefractive medium [1, 25, 30].

Using Eqs. (5) and (6), the expression for the nonlinear two-beam energy coupling constant (γ) inside a PR material can be written as

$$\gamma = \frac{\gamma_0\sigma_\mathrm{p}^2}{\sigma_\mathrm{p}^2+\Omega^2\varepsilon^2} \tag{8}$$

Equations (3) and (8) lead to the following expression for the gain (g),

$$g = \frac{(1+m)\exp(-\alpha l)}{1+m\exp\left(-\frac{\sigma_\mathrm{p}^2\gamma_0 l}{\sigma_\mathrm{p}^2+\Omega^2\varepsilon^2\varepsilon_0^2}\right)} \tag{9}$$

This amplification (i.e., two-beam coupling gain in the signal beam inside a PRO) is based on the following two main conditions: Firstly, the two-wave coupling gain has to overcome passive losses inside the oscillator, and secondly, the phase of the oscillating wave after one round-trip has to be an integral multiple of 2π.

In Eq. (2), the integration is carried over a round-trip beam path, N is an integer, $\Delta\psi_\mathrm{c}$ represents the phase shift in the presence of PR two-beam coupling, and it is given by [2, 25]:

$$\Delta\psi_\mathrm{c} = \frac{\Omega\tau}{2}\log_e\left(\frac{1+m}{1+m\exp(-\gamma l)}\right) \tag{10}$$

From Eq. (10), one can see that the PR phase shift in the signal beam is independent of the material absorption coefficient (α). Now, defining the cavity-length detuning parameter $\Delta\Gamma$ of a PRO is given by [25]:

$$\Delta\Gamma = 2N'\pi - \int k\mathrm{d}s \tag{11}$$

where N' is an integer chosen in such a way that $\Delta\Gamma$ lies between $-\pi$ and $+\pi$. Equations (2) and (11) yield:

$$\Delta\psi_\mathrm{c} = \Delta\Gamma + 2M\pi \tag{12}$$

where M is an integer. Thus, oscillation of PRO can be sustained only when the cavity-length detuning is compensated by the PR phase shift $\Delta\psi_\mathrm{c}$. This helps to fulfill the round-trip oscillator condition. Furthermore, the oscillating condition requires not only the loss of the beam intensity to be compensated for by the amplification [2, 19, 25]. With the help of Eqs. (1) and (9), the expression for the reflectivity (R) of the cavity mirrors is given by:

$$R = \frac{1+m\exp\left(-\frac{\sigma_\mathrm{p}^2\gamma_0 l}{\sigma_\mathrm{p}^2+\Omega^2\varepsilon^2\varepsilon_0^2}\right)}{(1+m)\exp(-\alpha l)} \tag{13}$$

Using Eqs. (10) and (13), the PR phase shift $\Delta\psi_\mathrm{c}$ in the signal beam of PRO can be written as:

$$\Delta\psi_{\mathrm{c}} = \frac{\Omega\varepsilon\varepsilon_0}{2\sigma_{\mathrm{p}}}\log_e[R\,\exp(-\alpha\,l)] \tag{14}$$

From Eq. (14), one gets the expression for the oscillation frequency shift Ω inside a PRO as:

$$\Omega \equiv\ \omega_{\mathrm{p}} - \omega_{\mathrm{s}} = \frac{2\sigma_p\,\Delta\psi_c}{\varepsilon\,\varepsilon_0\,(\alpha\,l - \log_e R)} = \frac{2\,\sigma_{\mathrm{p}}(\Delta\Gamma + 2M\pi)}{\varepsilon\,\varepsilon_0\,(\alpha\,l - \log_e R)} \tag{15}$$

Equation (15) represents the expression for the oscillation frequency shift Ω (frequency of oscillating beam) inside a PRO. The frequency of oscillating beam in a PRO is determined by the round-trip phase condition [Eq. (11)]. This is due to an additional phase shift that the oscillating beam acquires, which originates from PR beam coupling in PR material. From Eq. (15), one can also see that the frequency difference between the oscillating and pumping beams in a PRO depends on the optical cavity-length detuning ($\Delta\Gamma$). This dependence of frequency of oscillating beam on the optical cavity-length detuning supports for the PR phase shift associated with slightly non-degenerate two-wave mixing to satisfy the round-trip phase oscillation condition for the oscillating beam. From Eq. (15), it can also be concluded that the PRO would oscillate at the frequency different from the pump frequency by an amount directly proportional to the cavity-length detuning ($\Delta\Gamma$). This frequency detuning, of the order of 1–10 Hz in $\mathrm{BaTiO_3}$, is due to the grating motion in the crystal, which itself is inherently dependent upon the optical phases and amplitudes of the interacting beams in the oscillators and uniform electric field across the crystal [2, 12, 19, 25].

Now, using Eqs. (1), (4) and (8), one gets the expression for the intensity of oscillation $I_s(0)$ as:

$$I_s(0) = I_p(0)\left(\frac{R\,\exp(-\alpha\,l) - \exp\left(-\frac{\sigma_{\mathrm{p}}^2\,\gamma_0\,l}{\sigma_{\mathrm{p}}^2 + \Omega^2\varepsilon^2\varepsilon_0^2}\right)}{1 - R\,\exp(-\alpha\,l)}\right) \tag{16}$$

Equation (16) represents the expression for intensity of oscillating beam inside a PRO. However, the oscillation inside a PRO builds up almost regardless of the optical cavity length, its frequency being determined by the round-trip phase condition. The intensity of oscillation and the oscillation frequency shift are two most important parameters that characterize the performances of a PRO.

3. Results and discussion

The intensity of the oscillating beam ($I_2(0)$) [Eq. (16)] is a function of the energy beam coupling strength ($\gamma_0\,l$) of the PR material, absorption strength ($\alpha\,l$) of the PR material, product of the reflectivities (R) of the cavity mirrors and output coupler, dielectric constant (ε) and photoconductivity (σ_{p}) of the PR material.

The typical values of photoconductivity and dielectric constant for crystals which are representative of the most common classes of PR materials (BSO, BGO, BTO and SBN) in the photorefractive oscillator are given in Table 1.

The variation in the intensity of the oscillating beam with photoconductivity (σ_{p}) of the PR material for different values of $\gamma_0\,l$ (fixed $\Omega = 1.0\,\mathrm{Hz}$, $R = 80\%$, $\varepsilon = 12.0$ and $\alpha\,l = 0.1$), $\alpha\,l$ (fixed $\gamma_0\,l = 10$, $R = 80\%$, $\varepsilon = 12.0$ and $\Omega = 1.0\,\mathrm{Hz}$), ε (fixed $\gamma_0\,l = 10$, $\Omega = 1.0\,\mathrm{Hz}$, $R = 80\%$ and $\alpha\,l = 0.1$) and R (fixed $\gamma_0\,l = 10$, $\varepsilon = 12.0$, $\Omega = 1.0\,\mathrm{Hz}$ and $\alpha\,l = 0.1$) are shown in Fig. 2(a)–(d), respectively. It is clear from Fig. 2(a) that the oscillation starts from zero at the threshold ($\sigma_{\mathrm{p}} = 2\,\mathrm{pS/cm}$) and then increases with the photoconductivity of the PR material until saturation is reached. This means that the intensity of the oscillation beam is zero exactly at the threshold ($\sigma_{\mathrm{p}} = 2\,\mathrm{pS/cm}$) and is increasing gradually until the saturation level is reached with the increasing photoconductivity of PR material. However, it is interesting to note that the threshold is reached at lower photoconductivity of PR material with decreasing the energy coupling in the wave mixing of the two waves in materials. Thus, one can conclude that the threshold is reached at a lower value of photoconductivity ($\sigma_{\mathrm{p}} < 2\,\mathrm{pS/cm}$) by choosing small value of energy coupling in the wave mixing of the two waves in materials. It has

Table 1 Required material's parameters for BSO, BGO, BTO and SBN crystals

PR material's parameters	BSO [1, 31–35]	BGO [1, 31–35]	BTO [1, 31–35]	SBN [1, 31–35]
Crystal thickness l (cm)	1.0	1.0	1.0	1.0
Absorption coefficient α (cm^{-1})	0.65	0.52	1.0	0.3
Beam coupling constant γ_0 (cm^{-1})	10.0	0.4	15.0	7.0
Photoconductivity σ (pS/cm)	2.0	1.25	122.6	1000
Dielectric constant (ε)	56	40	47	800
Beam intensity ratio (m)	100	100	100	100
Frequency detuning Ω (Hz)	1.0	1.0	1.0	1.0

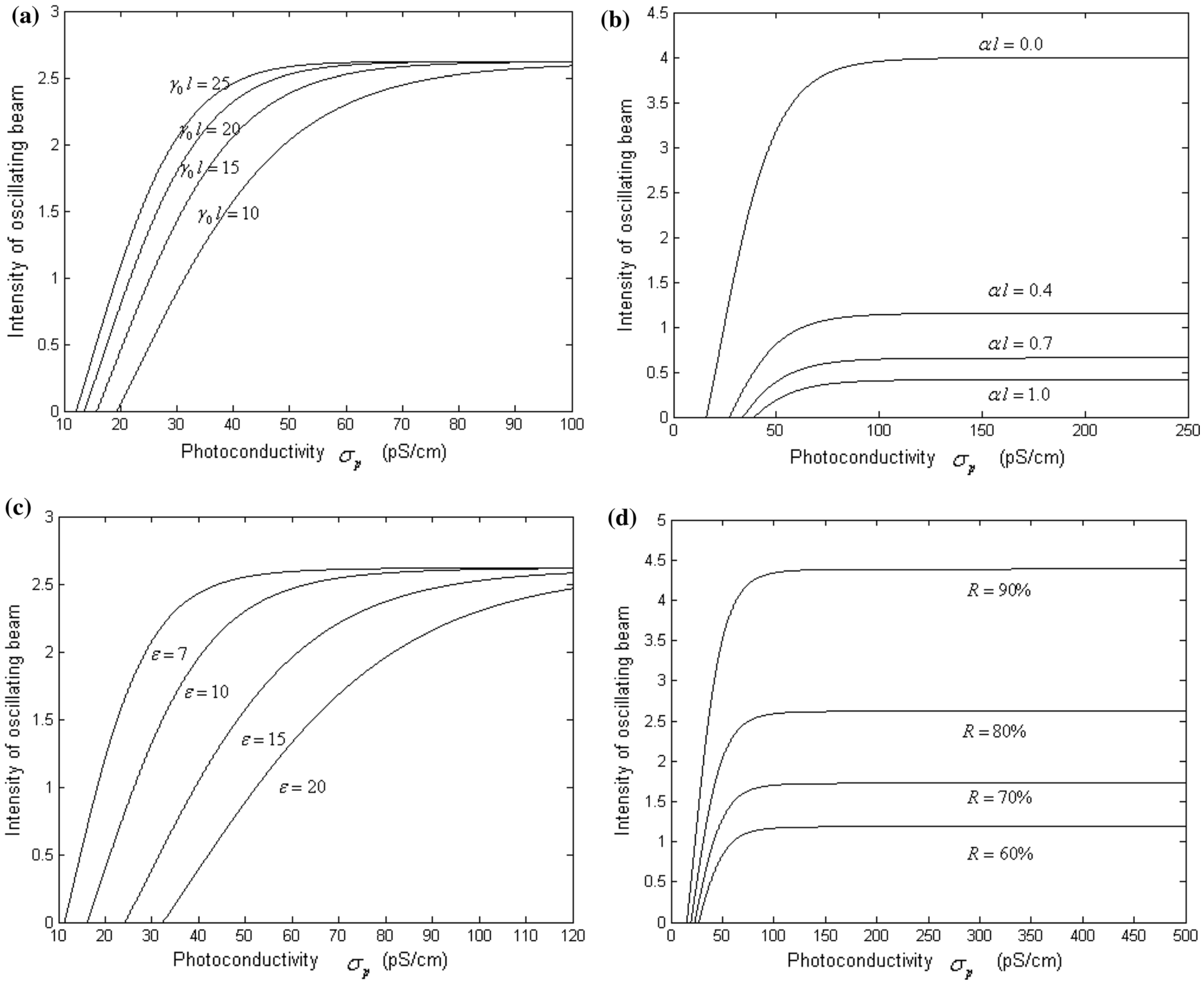

Fig. 2 Intensity of oscillating beam versus photoconductivity of PR crystal **(a)** for varying the energy beam coupling strength of PR crystal, **(b)** for varying the absorption strength of PR crystal, **(c)** for varying dielectric constant of PR crystal, **(d)** for varying the reflectivity of the cavity mirrors

also been observed that the threshold, which induces start of the oscillation intensity, occurs at a lower value of photoconductivity ($\sigma_p < 12$ pS/cm) with the increasing the energy beam coupling strength ($\gamma_0 l < 25.0$) of a PR material. This means that the threshold could be reduced to a larger extent by inserting a PR material of lower photoconductivity ($\sigma_p < 12$ pS/cm) and larger value of the energy beam coupling strength ($\gamma_0 l < 25.0$). Similar variation has been seen for the intensity of the oscillating beam with the absorption strength (αl), dielectric constant (ε) of PR material and reflectivity (R) of the cavity mirrors, which can be seen from Fig. 2(b)–(d). For the enhancement of the intensity of the oscillation and reducing the threshold in the oscillator, we select a PR material of lower absorption strength as well as lower photoconductivity [Fig. 2(c)] which means that the threshold at which the intensity of oscillation starts to increase could be minimized with the help of a PR material of lower absorption strength ($\alpha l < 0.1$) and lower photoconductivity ($\sigma_p < 20$ pS/cm). The plot of the intensity of oscillation with photoconductivity for PR material of different dielectric constants shows that the intensity of oscillation in the PRO could be increased by choosing PR material of lower dielectric constant ($\varepsilon < 7.0$) as well as lower photoconductivity ($\sigma_p < 11$ pS/cm) and same requirements are also needed for minimization of the threshold. On the basis of Fig. 2(a)–(d), one could conclude that for a given value of photoconductivity of PR material, the highly reflecting ($R > 90\%$) cavity mirrors are much effective parameter as compared to the other parameters (frequency detuning, absorption strength, energy beam coupling strength and dielectric constant) for the enhancement of the intensity of oscillation in the oscillator. It could also be seen that for a given value of σ_p, the intensity of oscillation in the PRO could be enhanced with the help of PR material having larger value of the energy beam coupling strength ($\gamma_0 l > 25$), lower value of absorption strength ($\alpha l < 0.1$), lower value of dielectric constant ($\varepsilon < 7.0$), lower value of photoconductivity ($\sigma_p < 25$ pS/cm) and by having highly reflecting ($R > 90\%$) cavity mirrors [Fig. 2(a)–(d)].

Figure 3(a)–(d), respectively, shows variation in the intensity of the oscillating beam $I_s(0)$ with the dielectric constant (ε) of PR material for different values of $\gamma_0 l$ (fixed $\Omega = 1.0$ Hz, $R = 80\%$, $\sigma_p = 100$ pS/cm and $\alpha l = 0.1$), αl (fixed $\gamma_0 l = 10$, $R = 80\%$, $\sigma_p = 100$ pS/cm and $\Omega = 1.0$ Hz), σ_p (fixed $\gamma_0 l = 10$, $\Omega = 1.0$ Hz, $R = 80\%$ and $\alpha l = 0.1$) and R (fixed $\gamma_0 l = 10$, $\varepsilon = 12.0$, $\Omega = 1.0$ Hz and $\alpha l = 0.1$). From Fig. 3(a), it is evident that with the increasing dielectric constant (ε) of PR material, the intensity of oscillation is constant over a certain region, and thereafter, it decreases rapidly with the increasing dielectric constant. However, it is interesting to note here that for a given value of ε, the intensity of oscillation decreases more rapidly with the decreasing the energy coupling of the wave mixing in PR materials which means that the constant region of the intensity of oscillation could be extended by keeping the energy coupling of the wave mixing in PR materials as high as possible. Thus, one could conclude that the fall in the intensity of oscillation can be reduced by keeping the energy coupling of the wave mixing as low as possible. Similar behaviors of the intensity of oscillation with absorption strength (αl), photoconductivity (σ_p) of PR material and reflectivity (R) of the cavity mirrors can be observed from Fig. 3(b)–(d). On the basis of Fig. 3(a)–(d), one could conclude that the intensity of oscillation could be enhanced with the help of PR crystal having lower

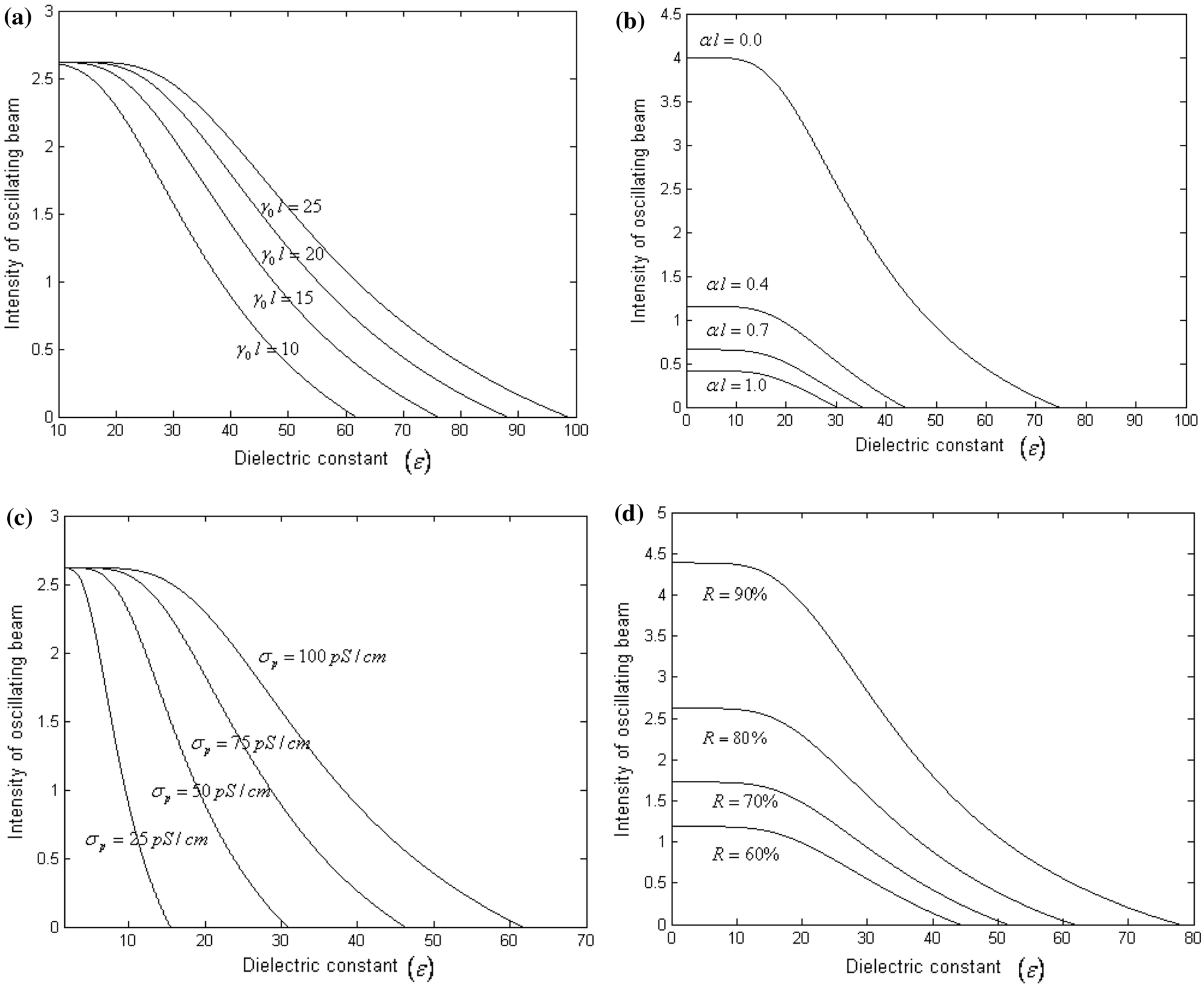

Fig. 3 Intensity of oscillating beam with dielectric constant of PR crystal **(a)** for the energy beam coupling strength of PR crystal ($\gamma_0 l = 10.0$, 15.0, 20.0 and 25.0); **(b)** for the absorption strength of PR crystal ($\alpha l = 0.0$, 0.4, 0.7 and 1.0); **(c)** for photoconductivity of PR crystal ($\sigma_A = 25$ pS/cm, 50 pS/cm, 75 pS/cm and 100 pS/cm); **(d)** for reflectivity of the cavity mirrors ($R = 60\%$, 70%, 80% and 90%)

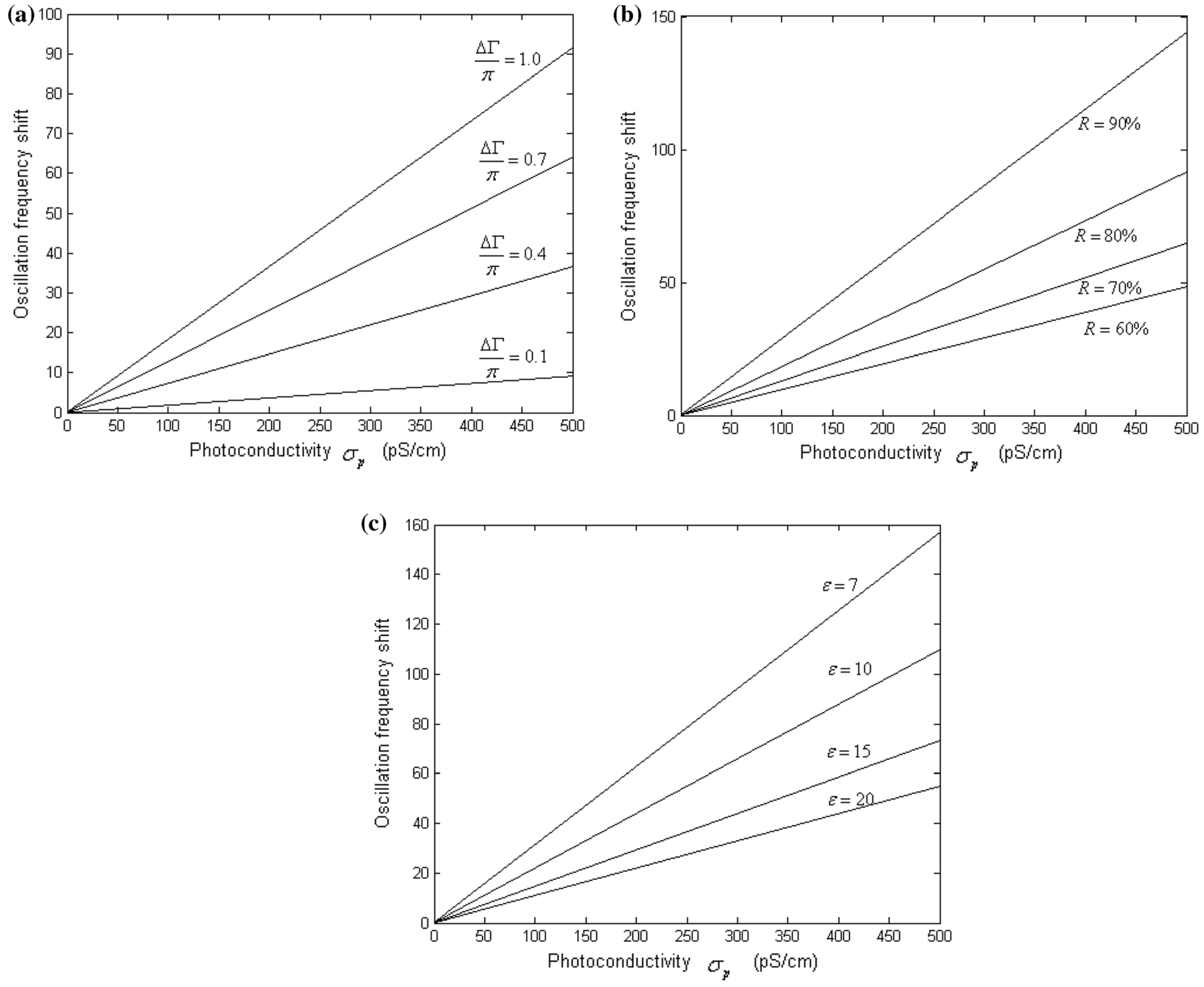

Fig. 4 Dependence of the oscillation frequency shift on photoconductivity of PR crystal **(a)** for varying the cavity-length detuning of the oscillator; **(b)** for varying the reflectivity of the cavity mirrors; **(c)** for varying dielectric constant of PR crystal

absorption strength ($\alpha l < 0.1$), lower dielectric constant ($\varepsilon < 20.0$), smaller value of the energy beam coupling strength ($\gamma_0 l < 10.0$), lower photoconductivity ($\sigma_p < 50$ pS/cm) and by having highly reflecting ($R > 90\%$) cavity mirrors. This greatly improves the performance and applications of a PRO in optical computing systems, e.g., self-scanning of a continuous dye laser, beam cleanup, associative memory systems, dynamics of the transverse pattern of the oscillating beam and in various other dynamic devices involving optical bistability and beam competition [2–29].

The oscillation frequency shift Ω (frequency of oscillation) [Eq. (15)] of the PRO is directly proportional to the cavity-length detuning. The variation in the frequency of oscillation (Ω) with photoconductivity (σ_p) of PR crystal for different values of $\frac{\Delta\Gamma}{\pi}$ (fixed $R = 80\%$, $\alpha l = 0.1$ and $\varepsilon = 12$), ε (fixed $R = 80\%$, $\frac{\Delta\Gamma}{\pi} = 1.0$ and $\alpha l = 0.1$) and R (fixed $\alpha l = 0.1$, $\frac{\Delta\Gamma}{\pi} = 1.0$ and $\varepsilon = 12$) is plotted in Fig. 4(a)–(c), respectively. From Fig. 4(a), one could see that the frequency of oscillation increases linearly with the increasing cavity-length detuning of the oscillator. It could also be seen that the frequency of oscillation can be increased by inserting PR material of higher photoconductivity ($\sigma_p > 500$ pS/cm). Similar variation in the oscillation frequency of the oscillator has been observed with the reflectivity (R) of the cavity mirrors and dielectric constant (ε), which can be seen from Fig. 4(b)–(c). For a given value of the photoconductivity of PR material, the oscillation frequency increases with the reflectivity (R) of the cavity mirrors [Fig. 4(c)]. Opposite behavior of the oscillation frequency is found in case of the dielectric constant [Fig. 4(c)]. This means that for a given value of σ_p, the magnitude of the oscillation frequency of the PRO could be enhanced by inserting PR crystal of lower value of the dielectric constant ($\varepsilon < 7.0$). On the basis of Fig. 4(a)–(c), it could be concluded that the magnitude of the oscillation frequency can be increased by selecting PR material of lower dielectric constant ($\varepsilon < 7.0$), higher photoconductivity ($\sigma_p > 500\,\mathrm{pS/cm}$) and highly reflectivity ($R > 90\%$) cavity mirrors provided that the cavity-length detuning $\left(\frac{\Delta\Gamma}{\pi} > 1.0\right)$ of the oscillator is higher. Hence, the oscillation frequency of a PRO could be controlled effectively by the dielectric constant, absorption strength, energy beam coupling strength and photoconductivity of PR materials.

4. Conclusions

Photoconductivity and dielectric constant dependence oscillation characteristics of a ring oscillator has been analyzed for the case of non-degenerate two-wave mixing in photorefractive materials. For a given value of photoconductivity of a PR material, the reflectivity ($R > 90\%$) of the cavity mirrors is a much effective parameter as compared to the other parameters (absorption strength, energy beam coupling strength and dielectric constant) for the enhancement of the intensity of oscillation in the oscillator. It has also been found that the magnitude of the oscillation frequency of a PRO can be increased by selecting PR material of lower dielectric constant ($\varepsilon < 7.0$), higher photoconductivity ($\sigma_p > 500\,\mathrm{pS/cm}$) and highly reflectivity ($R > 90\%$) cavity mirrors provided that the cavity-length detuning $\left(\frac{\Delta\Gamma}{\pi} > 1.0\right)$ of the oscillator is higher.

The intensity of oscillation and oscillation frequency of a PRO could be controlled by the dielectric constant, absorption strength, energy beam coupling strength and photoconductivity of a PR material which would greatly improve performance of a PRO and applications based on these PRO such as wave front color conversion, optical limiting, optical computing, beam cleanup, reconfigurable holographic interconnects, optical memories, logic gates, image amplification, image processing, correlators, associative memories, information processing, real-time processing, beam steering, beam combining, phase conjugation, resonators and pattern formation.

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