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Influence of photoconductivity and dielectric constant on an oscillation characteristics of a photorefractive resonator

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Abstract

In the present paper, photoconductive and dielectric dependence oscillation characteristics of a single photorefractive ring resonator have been studied for the case of non-degenerate two-wave mixing in photorefractive materials by employing the plane-wave approximation method. The influence of photoconductivity and dielectric constant of photorefractive materials on frequency of oscillation and the intensity of oscillating beam inside a single photorefractive ring resonator have been explored in details. It has been found that for a photorefractive material of fixed value of dielectric constant, the intensity of oscillation decreases more rapidly with the increasing frequency detuning of the resonator which means that the constant region of the intensity of oscillation could be extended by keeping the frequency detuning ($\Omega < 1.0\,Hz$) of the resonator as low as possible. This means that the fall in the intensity of oscillation can be reduced by keeping the frequency detuning ($\Omega < 1.0\,Hz$) of the resonator as low as possible.

Keywords: Photorefractive ring resonator, two-beam coupling and photorefractive materials

Introduction

The photorefractive effect is a phenomenon in which the local index of refraction is changed by the spatial variation of the light intensity. Such an effect was first discovered in 1966 [1-5]. The spatial index variation leads to the distortion of the wavefront, and such an effect was referred to as ‘‘optical damage’’[4-11]. The photorefractive effect has since been observed in many electro-optic crystals, including LiNbO3, BaTiO3, SBN, BSO, BGO, GaAs, InP, etc. Photorefractive materials are, byfar, the most efficient media for the recording of dynamic/static holograms [1-4]. In these media, information can be stored, retrieved and erased by the illumination of light. In addition to the holographic properties, energy coupling occurs between the recording beams and also between the reading beam and the diffracted beam [1-2]. 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. These features make them attractive materials for volume holographic data storage, image processing, optical interconnections, computing and neural networks [2–4,15–20]. Recently, the rapid development of optical fiber communication systems has stimulated the advancement of photorefractive devices [2-20].

Since photorefractive crystals can have large gain, they have been used as amplifying medium in the optical resonators. The photorefractive ring resonator has been used for real-time beam cleanup and has been proposed as a bistable device. Including additional nonlinear elements or multiple photorefractive interactions in a single ring, or allowing multiple rings to couple with one another, has led to increasingly sophisticated devices and dynamics [2, 7, 8, 13, 18]. Generalizations of the basic ring resonator have been used to demonstrate associative memories, flip-flop operation, controlled competitive dynamics, self-organized feature extraction, and topology-preserving feature mappings [2-9].

In this work we analyze the effect of photoconductivity and dielectric constant of the photorefractive materials on the intensity of oscillation and frequency of oscillation of the photorefractive resonator for the case of non-degenerate two-wave mixing in photorefractive materials by employing the plane-wave approximation method. It is seen that an efficient resonator can be realized even with moderate coupling constant if the absorption coefficient is low.

Theoretical Description

1. Photorefractive Resonator:

The simplest ring resonator geometry consists only of a cavity with three mirrors M_1, M_2 and M_3 and a photorefractive crystal pumped by a laser beam as shown in Fig.-1.

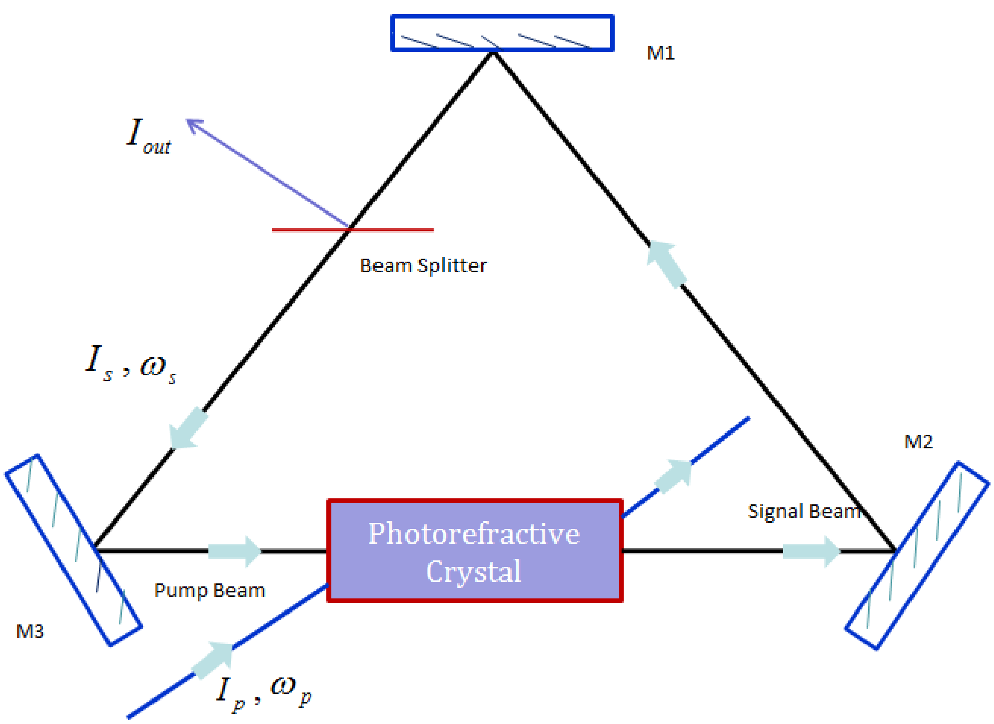

Fig.-1: Photorefractive Resonator

The inhomogeneities and impurities in the crystal produce beam fanning. The scattered light in the direction of signal beam is reflected by the cavity mirrors back into the crystal where amplification occurs by the process of two-wave mixing [2, 7, 13]. The oscillation beam builds up if the two-wave mixing gain is above a threshold value that is when the gain exceeds losses including the absorption in the crystal. Such a ring resonator has the capability of providing large amplification of weak signals and is very sensitive to minute changes in its length High powers can be achieved even with moderate values of two-beam coupling coefficient provided the losses are small. The scattered light away from the signal path will be lost. In the photorefractive ring configuration, the light propagation inside the cavity should be as the two-wave mixing is directional determined by the crystal symmetry, alignment and charge transport properties [2, 7, 8, 13, 18]. However, the unique feature of the photorefractive ring resonator is that the oscillation builds up almost regardless of the optical cavity length and oscillation can only be achieved for particular, limited geometries. This is due to an additional phase shift that the oscillating beam acquires, which originates from photorefractive coupling [2, 3, 13]. The frequency of oscillation and intensity of oscillation are determined by the round-trip phase condition [2, 7, 8, 13, 18].

2. Intensity of Oscillating Beam

The oscillation inside the photorefractive ring resonator starts from the noises generated by scattering and quantum fluctuation [2, 7-8]. In photorefractive crystals the scattering dominates the noise contribution. Initially there could be a little amount of light scattered along the direction of the ring resonator [2, 7, 8, 13, 18]. The two-wave mixing process in the photorefractive crystal amplifies this scattered light having frequencies differing from the frequency of the pump beam by ω $(\leq 30\text{Hz})$. As the intensity of this light in the resonator builds up, the parameter m decreases. The buildup of oscillation intensity leads to a saturation of the gain [2, 13, 18]. For the steady state oscillations, after each round trip the phase and intensity of the electric field of the signal beam must reproduce. The relative intensity of the signal beam with respect to the pump beam (i.e., intensity of oscillation) is given by [2, 7, 18]

$$I_R = \frac{I_s(0)}{I_p(0)} = \left[\frac{R\exp(-\alpha l) - \exp(-\gamma l)}{1 - R\exp(-\alpha l)}\right] \tag{1}$$

where, l is the crystal thickness of the photorefractive material, $I_s(0)$ is the intensity of the signal beam at $Z = 0$, $I_p(0)$ is the intensity of the signal beam at $Z = 0$, α is the absorption coefficient of the photorefractive material, R is the reflectivity of the cavity mirrors, γ is the non-linear two-beam energy coupling constant can be written as [13]

$$\gamma = \frac{\gamma_0}{1 + (\omega\tau)^2} = \frac{\gamma_0 \sigma_p^2}{\sigma_p^2 + \omega^2 \varepsilon^2} \tag{2}$$

where, $\omega (= \omega_p - \omega_s)$ is the frequency detuning (oscillation frequency shift) of the photorefractive resonator, 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 [13]

$$\tau = \frac{\varepsilon}{\sigma_p} \tag{3}$$

where, ε is the dielectric constant of the photorefractive material where, γ_0 is the coupling constant for the case of degenerate two-wave mixing (i.e., $\omega = \omega_p - \omega_s = 0$) and is given by the expression,

$$\gamma_0 = \frac{4\pi \, \Delta n_s}{\lambda \cos\theta} \tag{4}$$

where, Δn_s is the saturation value of the photo-induced index change, λ is the wavelength of the laser beam and θ is the half the angle between the beams inside the photorefractive medium [2, 7, 8, 13, 18]. With the help of Eq. (2) and (3), Eq. (1) can be written as,

$$I_R = \frac{I_s(0)}{I_p(0)} = \left[\frac{R\exp(-\alpha\, l) - \exp\left(-\dfrac{\gamma_0 \, \sigma_p^2 \, l}{\sigma_p^2 + \omega^2 \varepsilon^2} \right)}{1 - R\exp(-\alpha\, l)} \right] \tag{5}$$

Eq. (5) represents the expressions for the intensity of oscillation inside the photorefractive ring resonators.

3. Oscillation Frequency:

The difference between the frequency of the pump beam and oscillating beam (oscillation frequency of the resonator) ω is given by [2, 13, 18]

$$\omega(= \omega_p - \omega_s) = \frac{2\sigma_p (\Delta\Gamma + 2M\pi)}{\varepsilon(\alpha\, l - \log_e R)} \tag{6}$$

where, M is an integer and $\Delta\Gamma$ is the cavity-length detuning parameter of the resonator. Eq. (6) indicates that the frequency difference between the oscillating and pumping beams in a photorefractive resonator depends on the optical cavity-length detuning ($\Delta\Gamma$). This dependence supports for the photorefractive phase-shift associated with slightly non-degenerate two-wave mixing to satisfy the round-trip phase-oscillation condition for the oscillating beam [2, 7, 8, 13, 18]. From Eq. (6) it can also be seen that the photorefractive ring resonator will oscillate at the frequency different from the pump frequency by an amount directly proportional to the cavity-length detuning ($\Delta\Gamma$). However, the oscillation inside the ring resonator builds up almost regardless of the optical cavity length, its frequency being determined by the round trip phase condition [2, 13, 18]. The intensity of oscillation (Eq. (5)) and the oscillation frequency (Eq. (6)) are two most important useful parameters that characterizing the performances of a single photorefractive ring resonator.

Results and Discussion

The intensity of the oscillating beam (I_R) (Eq. (5)) is a function of the energy beam coupling strength ($\gamma_0 l$) of the PR material, absorption strength (αl) 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 variation of the intensity of the oscillating beam (threshold behavior of the oscillation intensity) with photoconductivity (σ_p) of the PR material for different values of Ω (fixed $\gamma_0 l = 10$, $R = 80\%$, $\varepsilon = 12.0$ and $\alpha l = 0.1$) is shown in the Fig.-2. It is clear from the Figure that the oscillation starts from zero at the threshold ($\sigma_p = 2\,pS/cm$) 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 ($\sigma_p = 2\,pS/cm$) 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 frequency detuning of the resonator. Thus, one can conclude that the threshold is reached at a lower value of photoconductivity ($\sigma_p < 2\,pS/cm$) by choosing lower value of the frequency detuning ($\Omega < 0.1Hz$) of the resonator.

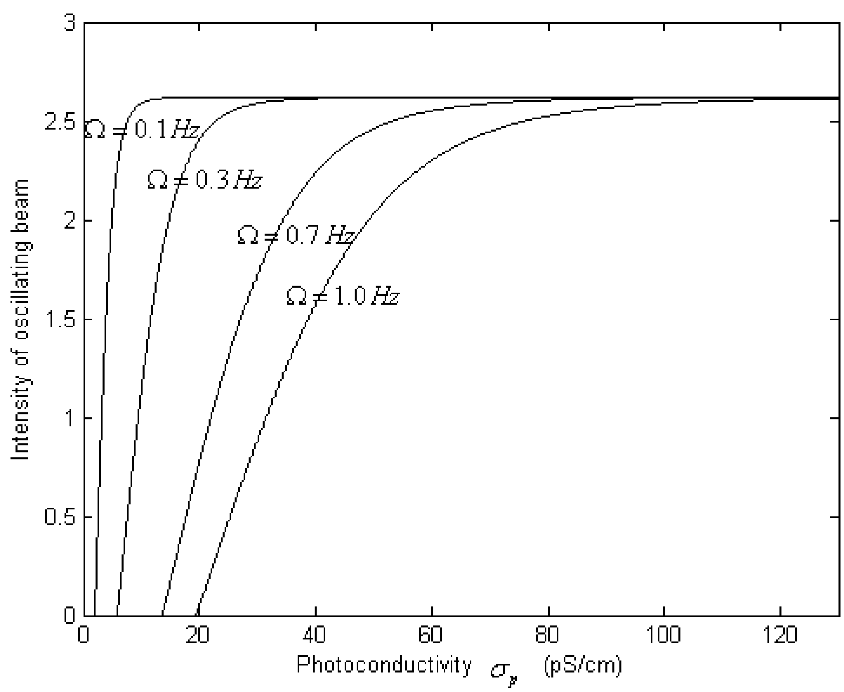

Fig.-2: Intensity of oscillating beam versus photoconductivity of PR crystal for varying the frequency detuning of the resonator

Fig.-3 shows the variation of the intensity of the oscillating beam $I_s(0)$ with the dielectric constant (ε) of PR material for different values of Ω (fixed $\gamma_0 l = 10$, $R = 80\%$, $\sigma_p = 100\, pS/cm$ and $\alpha l = 0.1$). From the Fig.-3 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 increasing frequency detuning of the resonator which means that the constant region of the intensity of oscillation could be extended by keeping the frequency detuning ($\Omega < 1.0\, Hz$) of the resonator as low as possible. Thus, one could conclude that the fall in the intensity of oscillation can be reduced by keeping the frequency detuning ($\Omega < 1.0\, Hz$) of the resonator as low as possible.

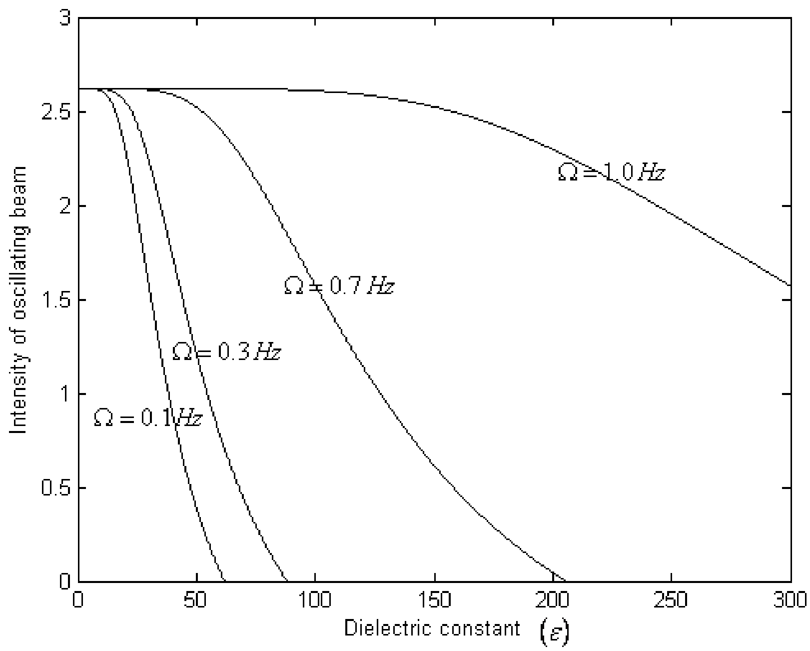

Fig.-3: Intensity of oscillating beam with dielectric constant of PR crystal for the frequency detuning of the resonator ($\Omega = 0.1\,Hz, 0.3\,Hz, 0.7\,Hz\ \&\ 1.0\,Hz$)

The oscillation frequency shift Ω (frequency of oscillation) (Eq. (6)) of the UPRR is directly proportional to the cavity-length detuning. In other words one could say that the UPRR will oscillate at a frequency different from the pump frequency by an amount directly proportional to the cavity-length detuning. The variation of the frequency of oscillation (Ω) with photoconductivity (σ_p) of PR crystal for different values of αl (fixed $R = 80\%$, $\frac{\Delta\Gamma}{\pi} = 1.0$ and $\varepsilon = 12$) is plotted in Fig.-4. From the Fig.-4, one could see that the frequency of oscillation increases linearly with the increasing photoconductivity of a PR material. It could also be seen that the frequency of oscillation can be increased by inserting PR material of lower absorption strength ($\alpha l < 0.5$) and higher photoconductivity ($\sigma_p > 500\, pS/cm$).

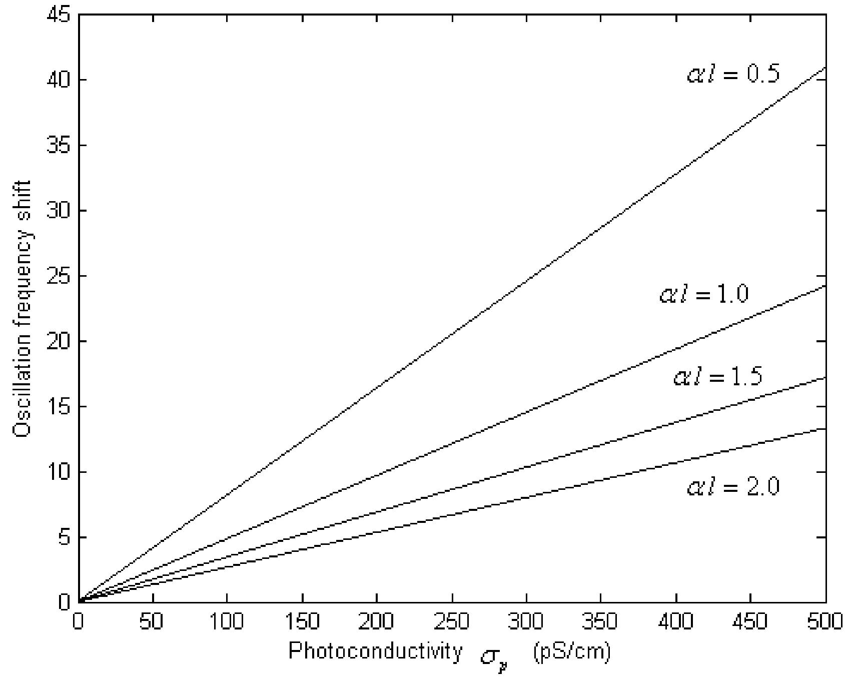

Fig.-4: Dependence of the oscillation frequency shift on photoconductivity of PR crystal for varying the absorption strength of PR crystal

The variation of oscillation frequency (i.e., oscillation frequency shift with respect to pump frequency) with dielectric constant (ε) of the photorefractive materials for different values of $\frac{\Delta\Gamma}{\pi}$ (fixed $R = 80\%$, $\alpha l = 1.0$, $\sigma_p = 5\, S/cm$, $\gamma_0 = 10\, cm^{-1}$) is shown in the Fig.-5. With increasing the dielectric constant (ε) of the photorefractive material the oscillation frequency of the single photorefractive ring resonator decreases very rapidly. For a given value of the dielectric constant (ε) of the photorefractive material, there is lowering in the oscillation frequency of the resonator which is higher for lower value of the cavity-length detuning of the resonator. On the basis of above Fig.-5, one may conclude that the magnitude of the oscillation frequency of a single photorefractive ring resonator can be increased for a photorefractive crystal having higher value photoconductivity as well as lower value of the dielectric constant by implementing the higher value of the reflectivity of the cavity mirrors in the ring resonator.

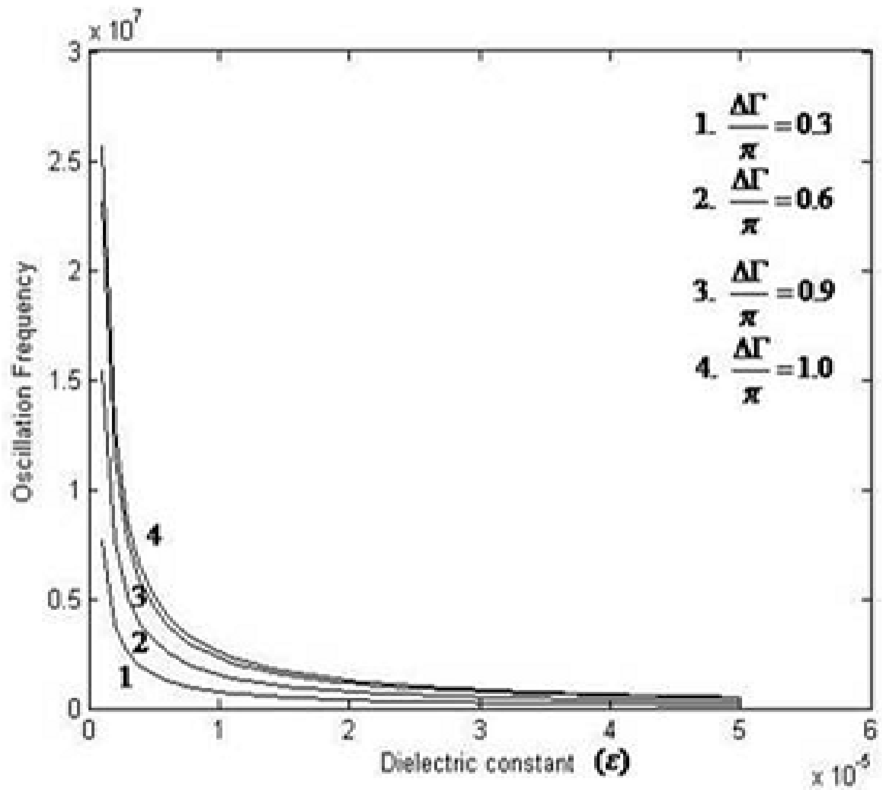

Fig.-5: Dependence of the oscillation frequency shift on dielectric constant of PR crystal for varying the cavity detuning of the resonator

Conclusions

In conclusion, photoconductive and dielectric dependence oscillation characteristics of a single photorefractive resonator have been explored in the case of non-degenerate two-wave mixing in photorefractive materials. It has been found that the magnitude of the oscillation frequency can be enhanced for a photorefractive crystal having lower value of the dielectric constant and higher value of the photoconductivity by increasing the cavity-length detuning of the ring resonator. For a photorefractive material of fixed value of dielectric constant, the intensity of oscillation decreases more rapidly with the increasing frequency detuning of the resonator which means that the constant region of the intensity of oscillation could be extended by keeping the frequency detuning ($\Omega < 1.0\,Hz$) of the resonator as low as possible. This means that the fall in the intensity of oscillation can be reduced by keeping the frequency detuning ($\Omega < 1.0\,Hz$) of the resonator as low as possible. This greatly improves the performance and applications of a single photorefractive ring resonator.

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