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One-dimensional modulation instability of broad optical beams in biased photorefractive–photovoltaic crystals under steady-state conditions

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Abstract

We present a comprehensive study of the one-dimensional modulation instability of broad optical beams in biased photorefractive–photovoltaic crystals under steady-state conditions. We obtain the one-dimensional modulation instability growth rate by globally treating the space-charge field and by considering distinction between values of E_0 in nonlocal effects and local effects in the space-charge field, where E_0 is the field constant correlated with terms in the space-charge field, which depends on the external bias field, the bulk photovoltaic effect, and the ratio of the optical beam's intensity to that of the dark irradiance. The one-dimensional modulation instability growth rate in local effects can be determined from that in nonlocal effects. When the bulk photovoltaic effect is neglectable, irrespective of distinction between values of E_0 in nonlocal effects and local effects in the space-charge field, the one-dimensional modulation instability growth rates in nonlocal effects and local effects are those of broad optical beams studied previously in biased photorefractive–nonphotovoltaic crystals. When the external bias field is absent, the one-dimensional modulation instability growth rates in nonlocal effects and local effects predict those of broad optical beams in open- and closed-circuit photorefractive–photovoltaic crystals.

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Optical spatial solitons, in particular photorefractive (PR) solitons, have attracted a great deal of attention because of their possible applications for optical switching and routing. They have been predicted and observed in Kerr media [1,2], in photovoltaic (PV) materials [3–6], in the screening configuration [7–10], in PR centrosymmetric materials [11–13], in anisotropic nonlinear media [14–16], etc. Recently, attention has been paid to multi-hump optical solions [17,18] and dipole-mode vector solitons [19,20] and to soliton collisions [21], all of which are proposed in biased photorefractive–nonphotovoltaic crystals. More recently, we have shown theoretically that the application of an external field enables steady-state solitons [22], soliton pairs [23], and vector solitons [24] in photorefractive–photovoltaic crystals. In particular, solitons in biased photorefractive–photovoltaic crystals change into screening solitons when the bulk PV effect is neglected, and PV solitons when the external field is absent [22]. However, modulation instability (MI) is an ordinary process that is inherent to most nonlinear systems [25]. It occurs in the same parameter region where solitons are observed, and it is considered as a precursor of soliton formation. Consequently, it would be of interest to know if the systems of these spatial solitons can also exhibit MI. The phenomena of MI was proposed in nonlocal nonlinear Kerr media [26,27] and in noninstantaneous nonlinear media [25,28]. On the other hand, the experimental observation of MI was presented in noninstantaneous nonlinear media [29,30]. In biased photorefractive–nonphotovoltaic crystals, the experimental evidence of MI is provided by considering local effects in the space-charge field [31], and soon thereafter the one-dimensional (1D) MI of quasi-plane-wave optical beams is investigated by globally treating the space-charge field [32]. Here, the space-charge field E_{sc} in biased photorefractive–nonphotovoltaic crystals is given by [32]

$$E_{sc} = E_0 \frac{1}{1+|U|^2}\left(1+\frac{\varepsilon_0\varepsilon_r}{eN_A}\frac{\partial E_{sc}}{\partial x}\right) - \frac{K_B T}{e} \times \frac{\partial\left(|U|^2\right)/\partial x}{1+|U|^2} + \frac{K_B T}{e} \times \frac{\varepsilon_0\varepsilon_r}{eN_A}\left(1+\frac{\varepsilon_0\varepsilon_r}{eN_A}\frac{\partial E_{sc}}{\partial x}\right)^{-1}\frac{\partial^2 E_{sc}}{\partial x^2}, \quad (1)$$

where $U(x,z)$ is assumed to be a bright-like beam, i.e., $|U|^2 = 0$ at $x \to \pm\infty$, N_A is the density of negatively charged acceptor, e is the electric charge, K_B is Boltzmann's constant, T is the absolute temperature, ε_r is the dielectric constant of the crystal, ε_0 is the permittivity of the vacuum, and E_0 represents the value of space-charge field in the dark regions (at $x \to \pm\infty$) of the photorefractive crystal. When the higher-order effects are neglectable, Eq. (1) takes the form

$$E_{sc} = E_0 \frac{1}{1+|U|^2}. \quad (2)$$

The constant field E_0 in Eqs. (1) and (2) can be computed from the potential condition [4] $\oint \boldsymbol{E}_{sc} \cdot d\boldsymbol{l} = 0$. However, 1D MI growth rate in [32] is obtained by globally treating the space-charge field, irrespective of distinction between values of E_0 in Eqs. (1) and (2). Moreover, we should also pay attention to the one-dimensional modulation instability of broad optical beams in biased photorefractive–photovoltaic crystals.

In this paper, we investigate the 1D MI of broad (quasi-plane-wave) optical beams in biased photorefractive–photovoltaic crystals under steady-state conditions. The 1D MI growth rate is obtained by globally treating the space-charge field and by considering distinction between values of E_0 in nonlocal effects and local effects in the space-charge field. This MI growth rate depends on the external bias field, the bulk photovoltaic effect, and the ratio of the optical beam's intensity to that of the dark irradiance. Moreover, our analysis indicates that when the bulk photovoltaic effect is neglectable, the 1D MI growth rates in nonlocal effects and local effects are those of broad optical beams studied previously in biased photorefractive–nonphotovoltaic crystals, when the external bias field is absent, the 1D MI growth rates predict those of broad optical beams in open- and closed-circuit photorefractive–photovoltaic crystals, and the 1D MI growth rate in local effects can be determined from that in nonlocal effects.

To investigate the 1D MI of a broad optical beam in a biased photorefractive–photovoltaic crystal under steady-state conditions, let us consider an optical beam that propagates in a photorefractive–