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Modulation instability in metamaterials with fourth-order linear dispersion, second-order nonlinear dispersion, and three kinds of saturable nonlinearites

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ABSTRACT

The linearized nonlinear propagation equation and its coefficients, gain spectrum of modulation instability (MI) in metamaterials (MMs) with fourth-order linear dispersion, second-order nonlinear dispersion, and three kinds of saturable nonlinearites, are analytically deduced by utilizing the linear stability analysis and Drude electromagnetic model. Then variations of gain spectra of MI with the normalized angular frequencies and the optical power densities are calculated in real units. In the negative refractive region, two kinds of gain spectra are discovered. The first (second) one is close to (far from) the zero perturbation frequencies and it corresponds to the lower (higher) normalized angular frequencies. Moreover, the second one has higher cutoff frequency, which is obviously beneficial to generation of high-repetition-rate pulse trains. While in the positive refractive region, only the first kind of gain spectra is found. With increase of the optical power densities, the peak gains and the spectral widths of MI increase before decrease, but they vary the most rapidly (slowly) for the exponential (conventional) saturable nonlinearities. The MI characteristics and their corresponding applications can be adjusted by several methods.

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1. Introduction

It is well known that modulation instability (MI) is a ubiquitous phenomenon in various nonlinear systems and thereby can occur in many branches of physics such as plasmas, Bose–Einstein condensation, fluid mechanics, and optics, etc. In optics, MI occurs as a result of the interaction between the nonlinearity and dispersion or diffraction and manifests itself as exponential growth of the weak perturbation under certain conditions which leads the continuous or quasi-continuous optical wave or the optical wave with uniform background to break up into various localized structures such as soliton-like pulse trains, multi-filament structures, or spatial–temporal solitions (light bullets). Therefore, MI is generally thought to be the precursor of all sorts of optical solitons. It has aroused continuous interest for decades for its physical significance and various beneficial or detrimental influences in high-speed optical communication systems, high-power laser systems, and so on. So far, MI in optics has been extensively investigated in various conventional optical materials, typical of them include the conventional fiber [1], fiber lasers [2], fiber grating [3], photorefractive crystals [4], and so on. Generally, as far as MI is concerned, people mainly pay attention to SPM- or XPM-induced MI [5] as well as various effects such as higher-order dispersion [6] and various higher-order nonlinear effects such as saturable nonlinearity [6,7], quintic nonlinearity [8], self-steepening effect, time-delayed Raman effect, etc., on MI in terms of its dispersion relation, instable condition, gain spectra, and its typical applications in generation of ultrashort pulse trans and supercontinuum.

It is all along an important goal for people to effectively manipulate the propagation of the electromagnetic wave or the movement of the photons at their own will and thereby successfully design more novel functional microwave devices or optoelectronic devices. Recent investigations indicate that various artificial composite materials are expected to achieve this goal. Typical of these materials are photonic crystals [9] and metamaterials (MMs) [10]. Among them, MMs are demonstrated to have many singular electromagnetic or optical properties such as negative or positive refractive effects, the reversal of Snell's law, the reversal of Doppler effect, the reversal of Cherenkov effect, and adjustable physical properties, etc. Those MMs which can exhibit negative refractive effects are also referred to as negative refractive MMs or left-handed materials.

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It is generally thought that occurrence of MI in new circumstances means new methods to generate and control optical solitons. Therefore, studies on MI are naturally extended to these singular materials in recent years. To date, many groups have investigated MI in MMs and some singular properties have been revealed. Concretely, besides the investigation on the nonlinear instability and its picture of the coupled plane wave solution [11], there are other studies on effects of higher-order linear dispersion [13], the first- and second-order nonlinear dispersion [12–14], saturable nonlinearity [12,14,15], quintic nonlinearity [16] on MI in MMs. However, most of recent studies have only taken into account the conventional saturable nonlinearity [12,14,15]. While previous studies have already confirmed that there exists different kinds of saturable nonlinearities which will influence MI considerably [17]. On the other hand, MMs can be constructed by periodic arrays of split-ring resonators (SRRs) and metallic wires. If further embedding the SRRs in a nonlinear dielectric which has extremely high nonlinear refractive index and is liable to exhibit the saturable nonlinear effect even for a moderate incident light intensity, one can construct the saturable nonlinear MMs. Besides, the local field enhancements in the SRRs arrays can be very intense, which also allows for enhanced nonlinear effects and then makes MMs exhibit saturable nonlinear effects more readily. In other words, embedding the SRRs in a certain saturable nonlinear dielectric such as the semiconductor $CdS_{1-x}Se_x$-doped glass material, one can construct saturable nonlinear MMs. Thus, it is worth studying MI in these saturable nonlinear MMs. Our previous studies on MI begin to consider different kinds of saturable nonlinearities [18,19]. On the basis of works mentioned above, MI in MMs with the fourth-order linear dispersion, second-order nonlinear dispersion, and three kinds of saturable nonlinearities, are analytically deduced and calculated in detail as well.

2. Theoretical model and linear stability analysis

After taking into account the saturable nonlinearity, first- and second-order nonlinear dispersion, fourth-order linear dispersion, and adopting a similar method of the establishment of the nonlinear propagation equation in MMs [14,18,20], one can obtain the following extended nonlinear propagation equation:

$$\frac{\partial A}{\partial z} = -\frac{i}{2}\beta_2\frac{\partial^2 A}{\partial T^2} + \frac{1}{6}\delta_3\frac{\partial^3 A}{\partial T^3} + \frac{i}{24}\delta_4\frac{\partial^4 A}{\partial T^4} +,$$
$$i\gamma_0\, Af\left(|A|^2\right) - \gamma_0 S_1\frac{\partial}{\partial T}\left[Af\left(|A|^2\right)\right] - i\gamma_0 S_2\frac{\partial^2}{\partial T^2}\left[Af\left(|A|^2\right)\right] \tag{1}$$

where the parameters β_2, δ_j (j = 3, 4), γ_0, $\Gamma = 1/P_{sat}$, P_{sat}, S_j(j = 1, 2), A, T, and z in Eq. (1) are the second-order group-velocity dispersion, the jth-order (j = 3, 4) group-velocity dispersion, the nonlinear coefficient, the saturable parameter, the saturable optical power, the jth-order (j = 1, 2) nonlinear dispersion, the slow varying amplitude of the optical field, the pulse time coordinate, and the propagation distance, respectively. The definitions of the equation coefficients can be seen in Ref. [14] and are omitted here. The function $f\left(|A|^2\right)$ stands for a certain kind of saturable nonlinearity. As Ref. [17] points out, there exist three kinds of saturable nonlinearities. In convenience, we call them conventional saturable nonlinearity (CSN), exponential saturable nonlinearity (ESN), and another kind of saturable nonlinearity (ASN), respectively. And the corresponding functions $f\left(|A|^2\right)$ in

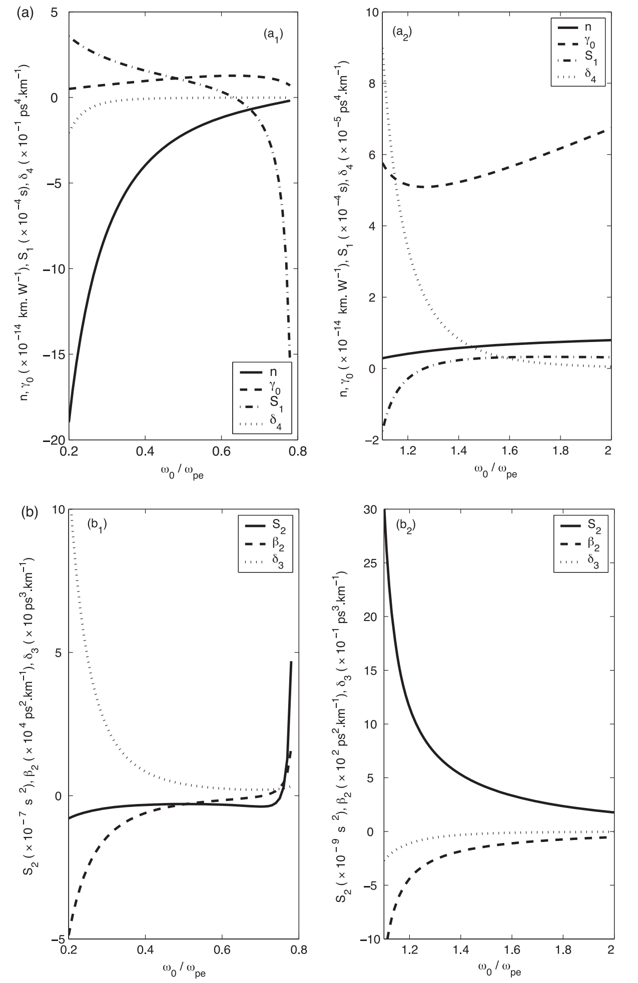

Fig. 1. Variations of the coefficients of Eq. (1) with the normalized frequency ω_0/ω_{pe} for $\omega_{pm}/\omega_{pe} = 0.8$.

Eq. (1) can be expressed as

$$f\left(|A|^2\right) = \begin{cases} |A|^2/\left(1+\Gamma|A|^2\right) & \text{(CSN)} \\ \left[1-\exp\left(-\Gamma|A|^2\right)\right]/\Gamma & \text{(ESN)} \\ |A|^2\left(2+\Gamma|A|^2/2\right)/\left[2\left(1+\Gamma|A|^2/2\right)^2\right] & \text{(ASN)} \end{cases}. \tag{2}$$

Adopting the famous Drude model to describe the electromagnetic characteristic of MMs and utilizing the definitions of the equation coefficients [14], the refractive index n and the corresponding coefficients of Eq. (1) at the carrier frequency ω_0 can be obtained as follows:

$$n(\omega_0) = \sqrt{1-\omega_{pe}^2/\omega_0^2}\sqrt{1-\omega_{pm}^2/\omega_0^2}, \tag{3}$$

$$\beta_2 = \frac{1}{cn\omega_0}\left[\left(1+3\omega_{pm}^2\omega_{pe}^2/\omega_0^4\right) - \frac{1}{n^2}\left(1-\omega_{pm}^2\omega_{pe}^2/\omega_0^4\right)^2\right], \tag{4}$$

$$\delta_3 = -\frac{12\omega_{pe}^2\omega_{pm}^2}{nc\omega_0^6}, \tag{5}$$

$$\delta_4 = \frac{60\omega_{pe}^2\omega_{pm}^2}{nc\omega_0^7}, \tag{6}$$

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