Optical Pulse Propagation in an Asymmetrical Nonlinear Direction Coupler and Limiting Effects

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We numerically investigate the light propagation in an asymmetrical nonlinear directional coupler(NLDC) composed one self-focusing core and one self-defocusing core. We show all-optical limiting features in the NLDC for both continuous wave and pulse cases and analyze the working conditions required.

Introduction

The NLDC composed of two cores with linear or nonlinear mismatch has been investigated by using the coupled-mode approaches and the beam propagation method in the case of continuous wave (CW) [1, 2, 3, 4, 5, 6]. Here we develope coupled equations which can describe the continuous wave and pulse propagation in an asymmetric NLDC composed of one self-focusing and one self-defocusing core [1, 3]. Analytical solutions are presented for the continuous wave case. The pulse case is numerically investigated by an extended split-step Fourier method. The study shows that, under some conditions, optical limiting can be achieved in this asymmetric NLDC for both continuous wave and pulse cases. Cascaded structures are investigated to improve the limiting characteristics. By varying the coupler length, one can adjust the limiting threshold and the output power conveniently.

Theory

The coupled equations for an asymmetric NLDC without loss can be directly written as[7, 8]

$$\frac{\partial A_1}{\partial z} = i\beta_{01}A_1 - \beta_{11}\frac{\partial A_1}{\partial t} - i\frac{\beta_{21}}{2}\frac{\partial^2 A_1}{\partial t^2} + \frac{\beta_{31}}{6}\frac{\partial^3 A_1}{\partial t^3} + i\gamma_1|A_1|^2A_1 + i\kappa A_2 - \eta\frac{\partial A_2}{\partial t} \quad (1a)$$

$$\frac{\partial A_2}{\partial z} = i\beta_{02}A_2 - \beta_{12}\frac{\partial A_2}{\partial t} - i\frac{\beta_{22}}{2}\frac{\partial^2 A_2}{\partial t^2} + \frac{\beta_{32}}{6}\frac{\partial^3 A_2}{\partial t^3} - i\gamma_2|A_2|^2A_2 + i\kappa A_1 - \eta\frac{\partial A_1}{\partial t} \quad (1b)$$

where $A_j(z,t)$ are the complex amplitudes of the field in channel j with j =1, 2; β_{0j} are the propagation constants; β_{1j}, β_{2j} and β_{3j} are the 1st order, 2nd order and 3rd order dispersion respectively; γ_j are the nonlinearity coefficients ; κ is the linear coupling coefficient [9] and η is the intermodal dispersion (IMD) [8] or the first-order coupling-coefficient dispersion in [10] and, for convenience in numerical analysis, we express the intermodal dispersion quantity as $\mathrm{IMD} = \eta/\kappa T_0$, where T_0 is the width of the input optical pulse.
Let $A_j = b_j/\sqrt{P_c}\exp(i\beta z)$ with $P_c = 4\kappa/\gamma$, which is the critical power [9], and $\beta = (\beta_{01} + \beta_{02})/2$. If one assumes $\beta_{11} = \beta_{12} = \beta_1$, $\beta_{21} = \beta_{22} = \beta_2$, $\beta_{31} = \beta_{32} = \beta_3$ and $\gamma_1 = \gamma_2 = \gamma$; applies the transformations $\tau = (t - \beta_1 z)/T_0$ and normalized corrdinate $Z = z\kappa$, then Eqs. (1) become

$$\frac{\partial b_1}{\partial Z} = i\delta b_1 - i\frac{\beta_2}{2\kappa L_D}\frac{\partial^2 b_1}{\partial \tau^2} + \frac{\beta_3}{6\kappa L'_D}\frac{\partial^3 b_1}{\partial \tau^3} + i4|b_1|^2b_1 + ib_2 - \mathrm{IMD}\frac{\partial b_2}{\partial \tau} \quad (2a)$$

$$\frac{\partial b_2}{\partial Z} = -i\delta b_2 - i\frac{\beta_2}{2\kappa L_D}\frac{\partial^2 b_2}{\partial \tau^2} + \frac{\beta_3}{6\kappa L_D'}\frac{\partial^3 b_2}{\partial \tau^3} - i4|b_2|^2 b_2 + ib_1 - \mathrm{IMD}\frac{\partial b_1}{\partial \tau}, \qquad (2b)$$

where $\delta = (\beta_{01} - \beta_{02})/(2\kappa)$ is the normalized propagation constant difference; $L_D = T_0^2/\beta_2$ and $L_D' = T_0^3/\beta_3$ are the second and third order dispersion length respectively.
By the extended split-step Fourier method (SSFM) as proposed in [11], one can solve Eqs. (2) numerically.
When $\kappa L_D \gg 1$, $\kappa L_D' \gg 1$ and $|\mathrm{IMD}| \ll 1$, Eqs. 2 will reduce to the CW case, that is

$$\frac{\partial b_1}{\partial Z} = i\delta b_1 + i4|b_1|^2 b_1 + ib_2 \qquad (3a)$$

$$\frac{\partial b_2}{\partial Z} = -i\delta b_2 - i4|b_2|^2 b_2 + ib_1. \qquad (3b)$$

Eqs. 3 can be analytically solved. In the case of single-input excitation:
Case 1: the power is initially launched into the self-defocusing waveguide only,

$$P_1(Z) = \frac{P_t}{1+(\delta+2P_t)^2}\sin^2\left\{[1+(\delta+2P_t)^2]^{1/2}Z\right\} \qquad (4a)$$

$$P_2(Z) = P_t - \frac{P_t}{1+(\delta+2P_t)^2}\sin^2\left\{[1+(\delta+2P_t)^2]^{1/2}Z\right\}. \qquad (4b)$$

Case 2: the power is initially launched into the self-focusing waveguide, $P_1(0) = P_t$ and $P_2(0) = 0$. In this case, the expressions of power evolution in the waveguides 1 and 2 are directly obtained by exchanging the subscripts of P_1 and P_2 in Eqs. 4. This implies that the power evolution in the asymmetric NLDC remains unchanged whenever the power is initially launched into the self-focusing waveguide or into the self-defocusing waveguide. This feature is quite different from the mismatched NLDC composed of two self-focusing waveguides or two self-defocusing waveguides, where non-reciprocity is observed [1].

Numerical Analysis

We investigated the working conditions of an asymmetric NLDC to function as an optical limiter. In Fig. 1, the normalized output power as a function of the input power in the asymmetric NLDC is shown. In the case of $\delta = -2.5$, the output is linearly proportional to the input as long as the input is below the limiting threshold. When the input exceeds the threshold power, the output becomes nearly constant over a range of power. In the case of $\delta = 2.5$, however, the output always shows some linear relationship with the input. Numerical analysis shows that an obvious limiting feature can be observed when $-2.5 < \delta \leq 0$ with appropriate coupling length.
Fig. 2 shows the limiting characteristics in a cascaded coupler structure. The dashed, solid and dash-dotted lines correspond to the single, second-order and third-order cascaded NLDC output. Numerical analysis shows that if the input power of the second coupler is below the limiting threshold power of the second coupler, there is no improvement to the limiting characteristics. However, when the output power of the first coupler is above the threshold power of the second coupler, the second coupler output becomes flatter than that of the first coupler due to the nonlinear restraining effects. Application of a cascaded structure, besides flattening the output, also enables to control the output power. Also Fig. 2 shows how the length of the third coupler influences the limiting characteristics in

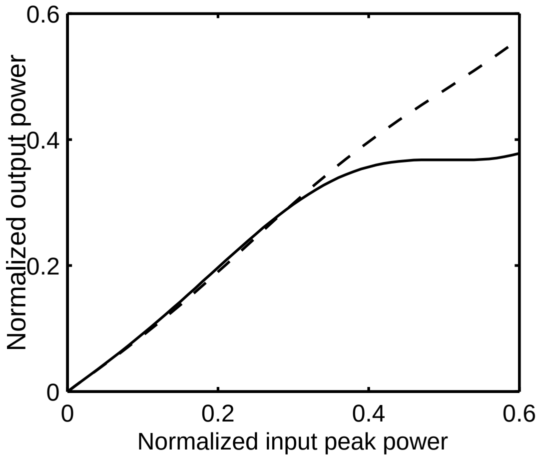

Figure 1: The input-output characteristics of a single-input asymmetric NLDC. Solid and dashed lines correspond to propagation constant mismatch $\delta = -2.5$ and $\delta = 2.5$.

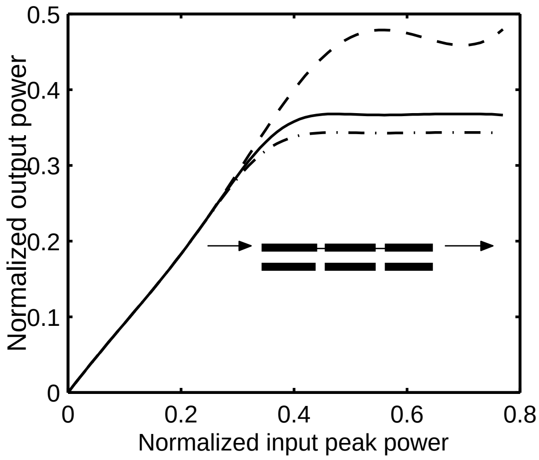

Figure 2: The limiting characteristics in the cascaded structure. Dashed, solid and dash-dotted lines correspond to the 1st, 2nd and 3rd coupler output. The couplers length are 0.9π, π and 1.1π, respectively.

a third-order cascaded NLDC. Obviously the limiting output power decreases as the third coupler length increases, but without degrading the limiting characteristics. This provides a simple but efficient way to control the limiting output power.

Fig. 3 shows that the pulse response of a third-order cascaded NLDC. We assumed $\kappa L_D = 1000$, $\kappa L'_D = 150000$, $\beta_2 > 0$ and IMD $= 0$. The dotted lines are the input pulses, the solid lines correspond to the outputs of the three couplers in the third-order cascaded NLDC with normalized coupler lengths 0.9π, π and 1.1π. Fig. 3 shows that as long as the input pulse power is below the limiting threshold, the output pulse will keep the same profile as the input pulse, namely a linear transmission system. While the input pulse peak power exceeds the limiting thresholds of these three couplers, the output pulse top will be tailored and the peak becomes flat, as the solid line 1, 2 and 3 in Fig. 3, but the rising and falling edges of the output pulse remain unchanged. In both cases, no pulse breakup occurs in this asymmetrical NLDC.

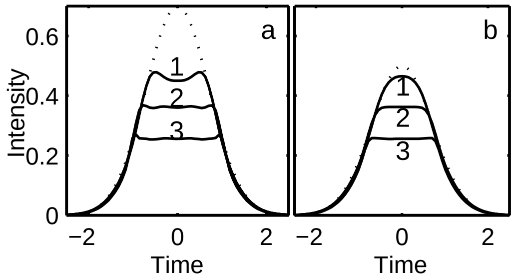

Figure 3: Temporal profiles of the input-output pulses. Dotted line is the input pulse profile. Solid line 1, 2 and 3 are the output of the 1st, 2nd and 3rd coupler. a. input $b_1(0,\tau) = 0.7\exp(-\tau^2)$ and $b_2(0,\tau) = 0$, b. input $b_1(0,\tau) = 0.5\exp(-\tau^2)$ and $b_2(0,\tau) = 0$

Conclusion

We have demonstrated limiting features in the asymmetric NLDC for both continuous wave and pulse cases and analyzed the working conditions required. Cascaded NLDCs are also investigated to improve the limiting feature. The limiting threshold and the output power can be adjusted by varying the coupler length. In the case of a pulse input, a flat-top pulse is generated when the peak power of the incident pulse comes above the limiting threshold power, but almost lossless linear behavior is shown as long as the peak power is below the limiting threshold. Unlike in a conventional NLDC, in both cases the rising and falling edges of the output pulse overlap the input pulse. No pulse breakup is observed.

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