Subpicosecond Rectangular Optical Pulse Generator Using Cascaded Nonlinear Directional Couplers

W. Wang[1], Y. Wang[2], K. Allaart[1] and D. Lenstra[1]

Department of Physics and Astronomy, Vrije University Amsterdam, De Boelelaan 1081, 1081 HV and COBRA Research Institute, Eindhoven, The Netherlands[1], Agilent Technologies, Singapore [2],

We demonstrate numerically a novel method to generate rectangular optical pulses by nonlinear directional couplers. Single and cascaded coupler structures are investigated and it is shown that femtosecond rectangular-like pulses can be generated in a second-order cascaded nonlinear directional coupler (NLDC) and subpicosecond ideal rectangular pulses could be achieved in a third-order cascaded NLDC. The influences of intermodal dispersion and higher order dispersion are included in the numerical analysis.

Introduction

The generation of ultrashort pulses with rectangular shape is required for a wide range of pump probe experiments such as to study carrier dynamics, or coherent excitation and control of optically induced quantum states. Also it is desirable to improve the performance of optical switches by reducing the switching power, and by making the switching transition sharper as well as creating a larger extinction ratio [1]. Ultrashort rectangular pulses have been generated by Fourier synthesis techniques [2, 3]. While impressive results are possible with this technique, the hardware required to synthesize the desired spectrum usually is bulky, lossy and expensive and does not lend itself to easy integration with waveguide devices [3]. We report a novel method to generate femtosecond rectangular optical pulses by employing the nonlinear directional coupler (NLDC).

Theory

In our recent work we found that the product of the dispersion length and coupling coefficient κL_D is the key parameter of a NLDC. The pulse coupling behavior mainly depends on κL_D rather than on the input pulse shape when the third-order dispersion and intermodal dispersion are negligible [4]. Also it was found that the pulse switching performance, regarding the energy transfer, is in a NLDC similar to the case of a CW when $\kappa L_D > 10$. In a normal coupler with second order dispersion coefficient $\beta_2 = -6.5 ps^2/km$ and half-beat length $L_c = 1mm$, κL_D can be 55, even for a 15 fs optical pulse. Therefore, an ultrashort pulse can exhibit the same energy coupling behavior in a NLDC as in the case of a CW. Based on this, we propose a novel method to generate ideal ultrashort rectangular optical pulses by employing a NLDC.
The pulse propagation in a coupled nonlinear optical waveguide can be described by coupled nonlinear Schrödinger equations. The time-dependent nonlinear equations governing the propagation of pulses in a NLDC can be expressed as [4, 5]

$$\frac{\partial A_j}{\partial Z} = -i\frac{\mathrm{sgn}(\beta_2)}{2\kappa L_D}\frac{\partial^2 A_j}{\partial \tau^2} + \frac{\mathrm{sgn}(\beta_3)}{6\kappa L'_D}\frac{\partial^3 A_j}{\partial \tau^3} + i\frac{\gamma}{\kappa}|A_j|^2 A_j + iA_{3-j} - \frac{\eta}{\kappa T_0}\frac{\partial A_{3-j}}{\partial \tau},$$

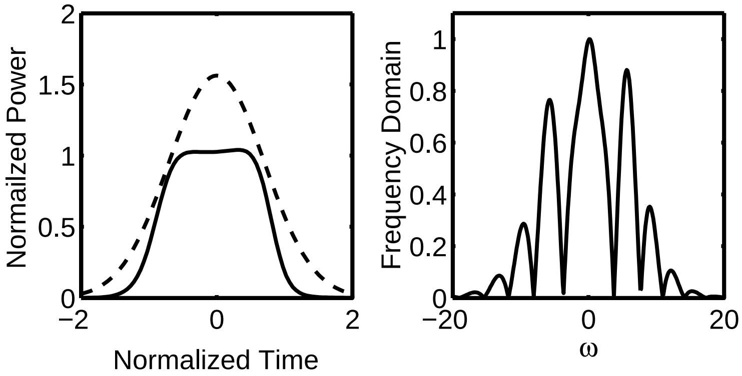

Figure 1: Pulse shape from the launching channel of a single NLDC in the time and the frequency domain.

where A_j is the slowly-varying envelop amplitude of the mode in channel j of the NLDC with $j = 1,2$; β_1, β_2, and β_3 are the first, second and third order dispersion coefficients, respectively, γ is the nonlinearity coefficient, κ is the linear coupling coefficient, $L_D = T_0^2/|\beta_2|$ is the second order dispersion length, $L'_D = T_0^3/|\beta_3|$ is the third order dispersion length [6], $\tau = (t - \beta_1 z)/T_0$, with T_0 the width of the input optical pulse; z is the coordinate in the direction of propagation and $Z = z\kappa$ is the normalized length of the coupler; η is the intermodal dispersion [7]. We define the parameter $IMD = \eta/T_0\kappa$ for convenience in the numerical analysis.

Numerical Analysis

Fig. 1 shows the temporal profile and the spectrum of the output pulse from the launching channel of a NLDC with $\beta_2 > 0$. The dotted line is the input Gaussian pulse and the solid line is the output pulse shape. The simulation was done using Eq. (1) , where we assumed $\kappa L_D = 40$, $\kappa L'_D = 600$ and $IMD = -0.01$. The normalized length of the coupler is 0.55π, and the input pulse is $a_1(0,\tau) = 1.15\exp(-\tau^2/2)$, while $a_2(0,\tau) = 0$.
It is obvious that a Gaussian input pulse can form a flat-top pulse in a NLDC waveguide under certain conditions. Numerical analysis shows that a flat-top pulse can be generated in a NLDC with $50 > \kappa L_D > 10$ in the normal dispersion regime, or with $\kappa L_D > 200$ in the normal and abnormal dispersion regimes when a Gaussian pulse is launched in. We also investigated the influence of $\kappa L'_D$ and IMD on the output pulse shape in a NLDC. We find that, to generate a symmetrical flat-top pulse, the following conditions should be both fulfilled: $\kappa L'_D \geq 600$ and $|IMD| \leq 0.03$ when $50 > \kappa L_D > 10$, or $\kappa L'_D \geq 6000$ and $|IMD| \leq 0.03$ when $\kappa L_D > 200$.
Clearly, in Fig. 1 a single NLDC generated a flat top pulse, but the rising and falling time of the edges are rather long compared to the pulse width. To generate a flat-top and steep-edge rectangular-like pulse, a second-order cascaded NLDC may be applied. Fig. 2 shows the temporal profile of the output pulse of a second-order cascaded NLDC and its spectrum. The input pulses are $a_1(0,\tau) = 1.2\exp(-\tau^2/2)$ and $a_2(0,\tau) = 0$. The normalized coupler length of both couplers is $\pi/2$, while $\kappa L_D = 1500$, $\kappa L'_D = 45000$, and $IMD = -0.003$. Fig. 2a shows the output pulses from the first and the second coupler of such a second-order cascaded NLDC. It is obvious that the output pulse has much steeper

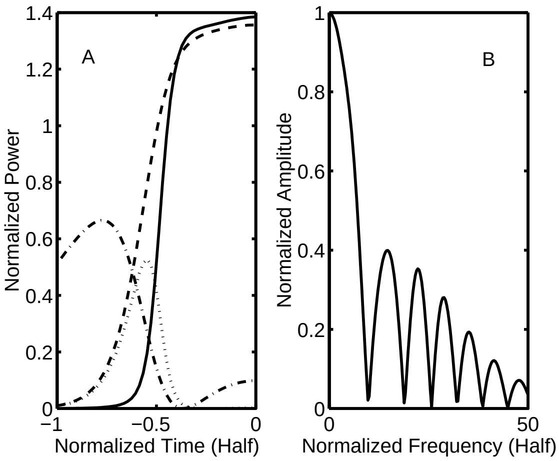

Figure 2: (a) Temporal profile of the output pulse from of a second-order cascaded NLDC, where the dashed line and solid line correspond to the 1st coupler and 2nd coupler respectively. (b) Output pulse spectrum from the launching channel of the second coupler in the second-order cascaded NLDC.

rising and falling edges in a second-order cascaded NLDC than in a single NLDC. Fig. 2b shows the spectrum of the output pulse from the launching channel of the second coupler. It can be seen that the spectrum of the output pulse is a *sinc*-like function. Numerical analysis shows that to generate a rectangular-like pulse in a second-order cascaded NLDC, the following working conditions should be met: $\kappa L_D \geq 1500$, $\kappa L'_D \geq 45000$ and $|IMD| \leq 0.008$. In a case with $\beta_2 = -6.5\text{ps}^2/\text{km}$, $\beta_3 = 0.1\text{ps}^3/\text{km}$ at $\lambda = 1.3\mu\text{m}$ and $L_c = 1\text{mm}$, T_0 will be larger than 80fs, 140fs, and 70fs respectively. Therefore 140fs is the minimum working pulse width. The output pulse is compressed so that an about 50fs rectangular-like pulse may be generated in this second-order cascaded NLDC.

The output pulse shapes of second-order cascaded NLDCs suggest that higher-order cascaded NLDCs could generate an ideal rectangular pulse by cutting the edges even steeper. Our numerical analysis confirms this the expectation. We adopt a cascaded NLDC consisting of three couplers C_1, C_2 and C_3 of which the output of the former is input for the latter one.

In Fig. 3 we show the temporal profile of the output pulses of C_1, C_2, and C_3. The input of C_1 is $a_1(0,\tau) = 1.2\exp(-\tau^2/2)$ and $a_2(0,\tau) = 0$. The parameters for all three NLDCs are: $\kappa L_D = 100000$, $\kappa L'_D = 1200000$, $IMD = -0.003$ and normalized coupler length $\pi/2$. The dashed line, dash-dotted line and solid line are the C_1, C_2, and C_3 output pulse shape, respectively, and the dotted line is the input Gaussian pulse. Obviously from the C_1 to the C_3 output, the pulse shape is approaching an ideal rectangular pulse. The relation between the pulse width, power and κL_D: $\kappa L_D \propto T_0^2 \cdot P_c$ shows that large κL_D limits this method to the broad pulse width or high power regime. According to our numerical analysis, the required minimum input pulse width for a third-order cascaded NLDC with coupling length $L_c = 1\text{mm}$, $\beta_2 = 15\text{ps}^2/\text{km}$, $\beta_3 = 0.1\text{ps}^3/\text{km}$ and $\lambda = 1.06\mu\text{m}$ will be 1ps, limited by κL_D, and the output pulse width will be in the subpicosecond regime due to the pulse compression in the NLDC.

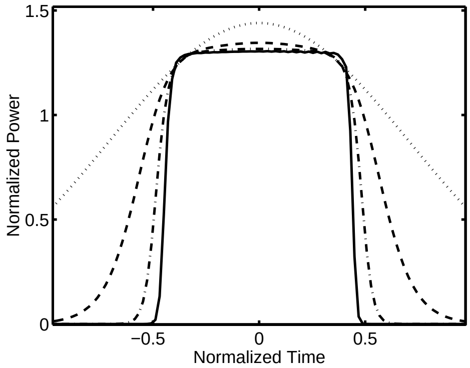

Figure 3: Temporal profile of the output pulse from the launching channel of a third-order cascaded NLDC.

Conclusion

We propose a novel method to generate ultrashort optical rectangular pulses by nonlinear directional couplers. Single and cascaded NLDCs structures are numerically investigated and it is shown that a femtosecond rectangular-like pulse can be generated in a second-order cascaded NLDC while a subpicosecond ideal rectangular pulse can be achieved in a third-order cascaded NLDC.

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