A Waveguide Directional Coupler Based on Quantum Nanostructures with Decay Interference

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SCOPE OF THIS WORK: Optical nonlinearity plays an important role in the switching properties of the two-waveguide directional coupler system and leads to several interesting phenomena, such as soliton switching [1]. In a particular study some years ago Wabnitz and co-workers [2, 3] proposed and analyzed the switching characteristics of a nonlinear two-waveguide directional coupler where the constituent waveguides are made of a linear host material doped with two-level type resonant impurities. For a tapered waveguide structure and for the propagation of ultrashort pulses they showed that this device can work as a self-induced transparency soliton switch, with digital transmission characteristics.

Controlled propagation of laser pulses and the creation of slow light have been studied in several quantum nanostructures that exhibit decay interference, see e.g. refs. [4–7]. In this work, along the lines of the work of Wabnitz and co-workers [2, 3], we propose a two-waveguide directional coupler that consists of two parallel waveguides that are put close to each other so evanescent coupling can occur. The constituent waveguides are made of a linear host material doped with a quantum system that exhibits decay interference (for example, quantum dot impurities that exhibit decay interference [8]). The system can also be realized with the constituent waveguides being made of multiple semiconductor quantum well systems with tunnelling induced interference [9, 10]. For the analysis of the propagation dynamics of electromagnetic pulses in the proposed device we use a modified coupled-mode theory analogous to that of ref. [3]. Solving analytically, under proper approximations, and numerically the generalized coupled Maxwell-Bloch equations we show that the dynamics of the pulse propagation depends critically on the parameters of the quantum system and on the duration of the pulse. Loss-free propagation and slow light switching between the two waveguides are found to occur in the studied system.

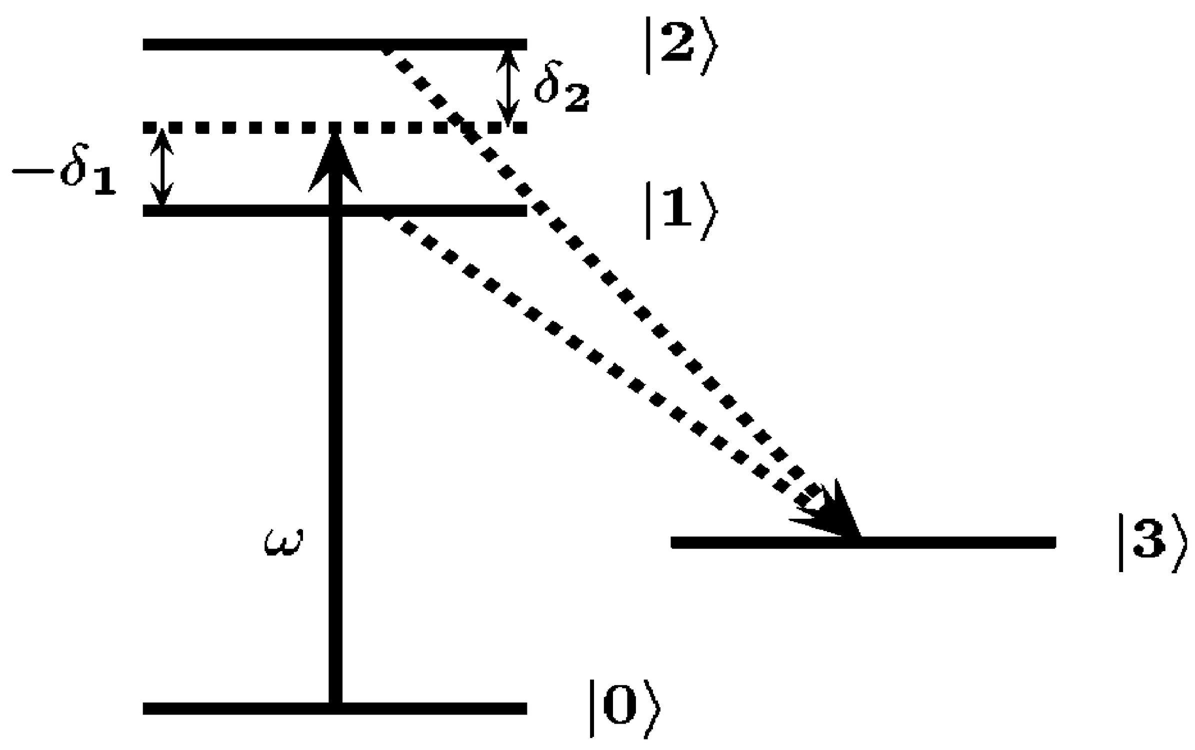

Figure 1: (Left) The quantum system under consideration has a ground state, |0>, two closely lying excited states, |1>, |2>, that can couple to the ground state by electric dipole coupling. The two states decay via spontaneous emission to the same state |3>. This is a quantum model for atoms, molecules or semiconductor quantum dots. The system can be also realized if the waveguides are made of multiple asymmetric double quantum wells with tunneling induced interference, similar to those described in refs. [7, 9, 10].

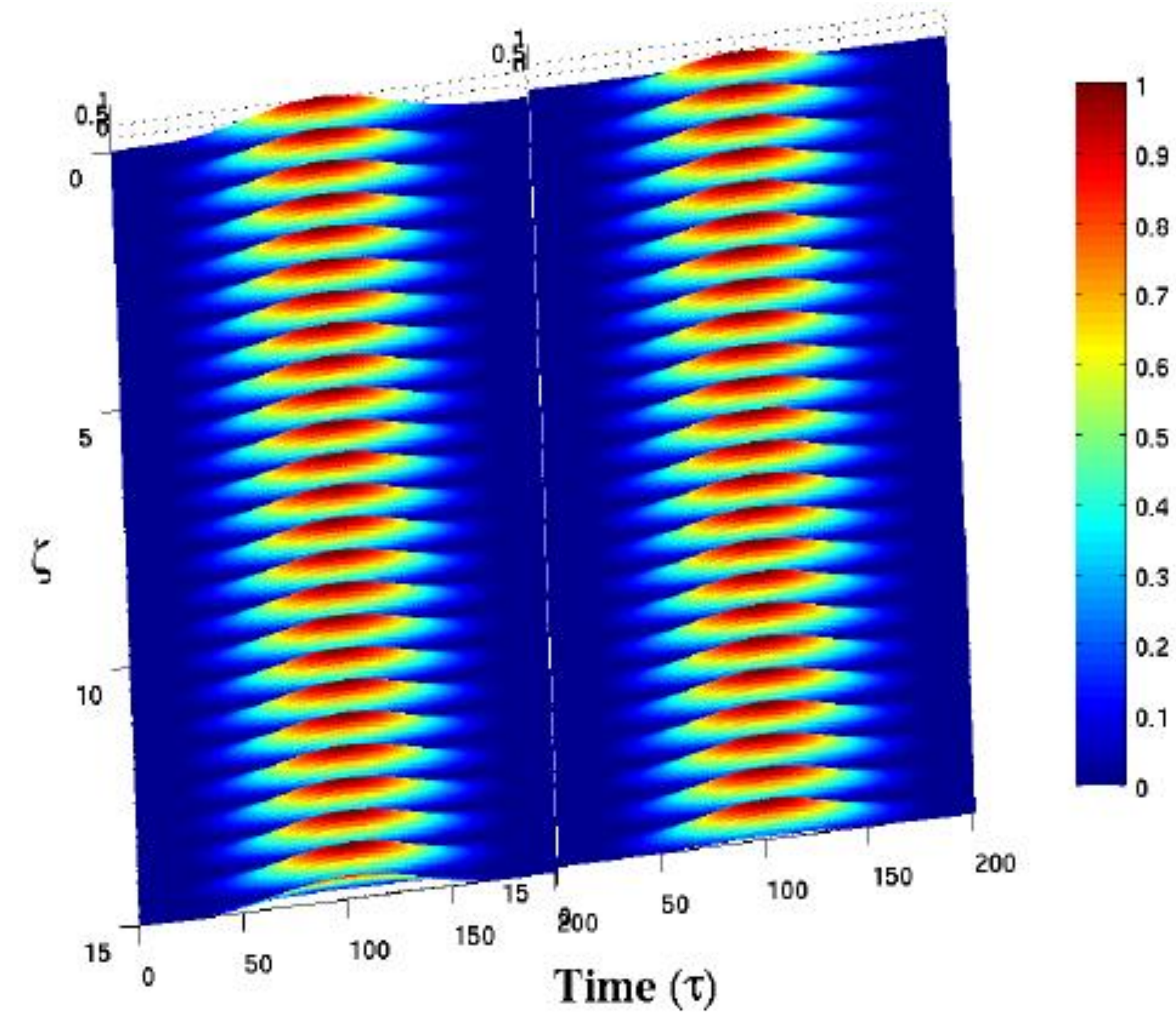

Figure 2: (Left) The magnitude-squared of the pulse envelope in the two waveguides as a function of time and distance for weak, initially sin-squared envelope, laser pulses. The parameters of the quantum system are taken in order to fulfill the trapping conditions (the conditions that lead to the dark state of the system, see Eqs. (6) and (7) of ref. [4]). Here, a long pulse is used, that leads to completely adiabatic interaction between the light pulse and the quantum system. So, the quantum system becomes fully transparent. In this case the pulse switching is determined completely by the evanescent light coupling between the two waveguides.

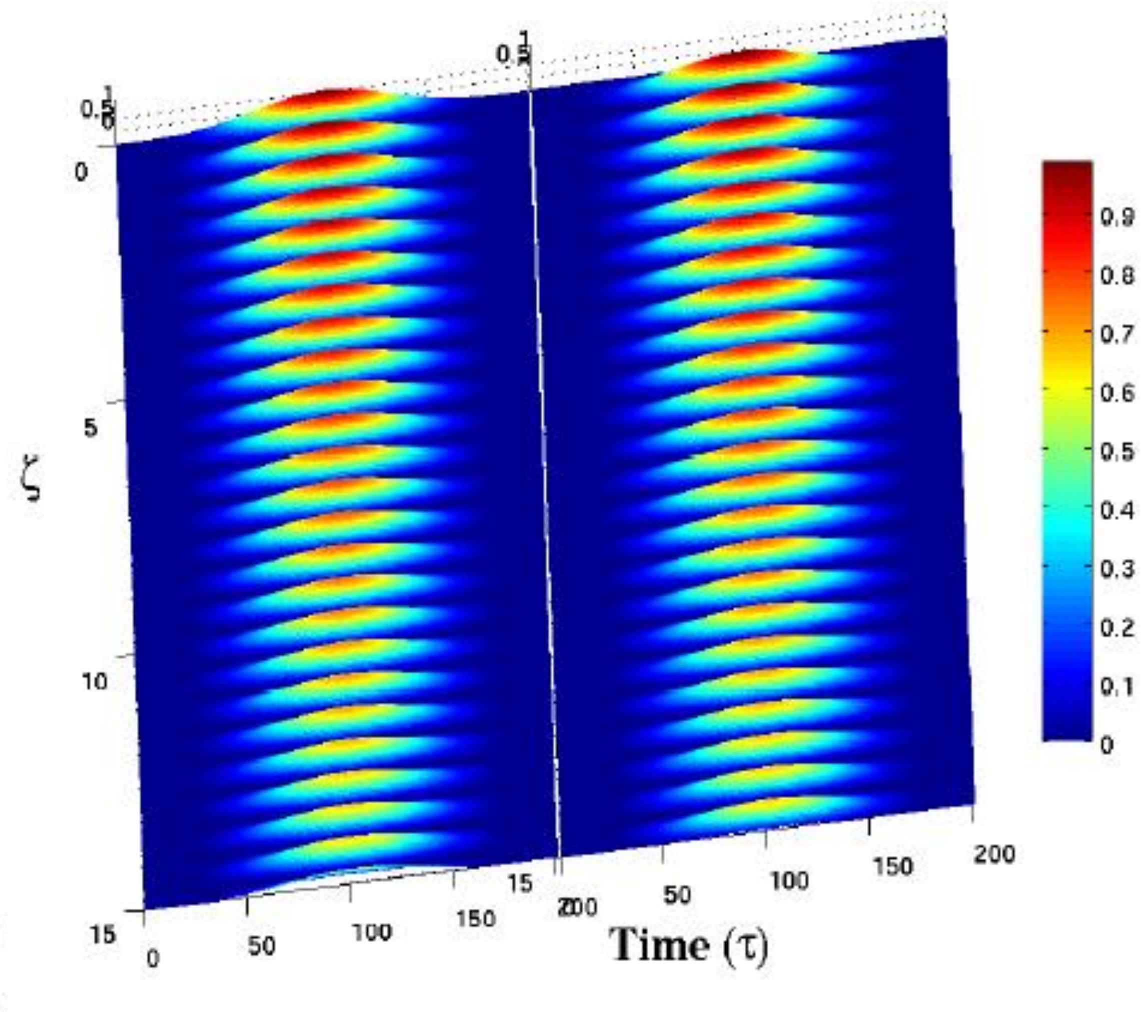

Figure 3: (Left) The same as in Fig. 2 without fulfilling the trapping conditions. A gradual absorption of the laser pulse is obtained as it switches between the two waveguides.

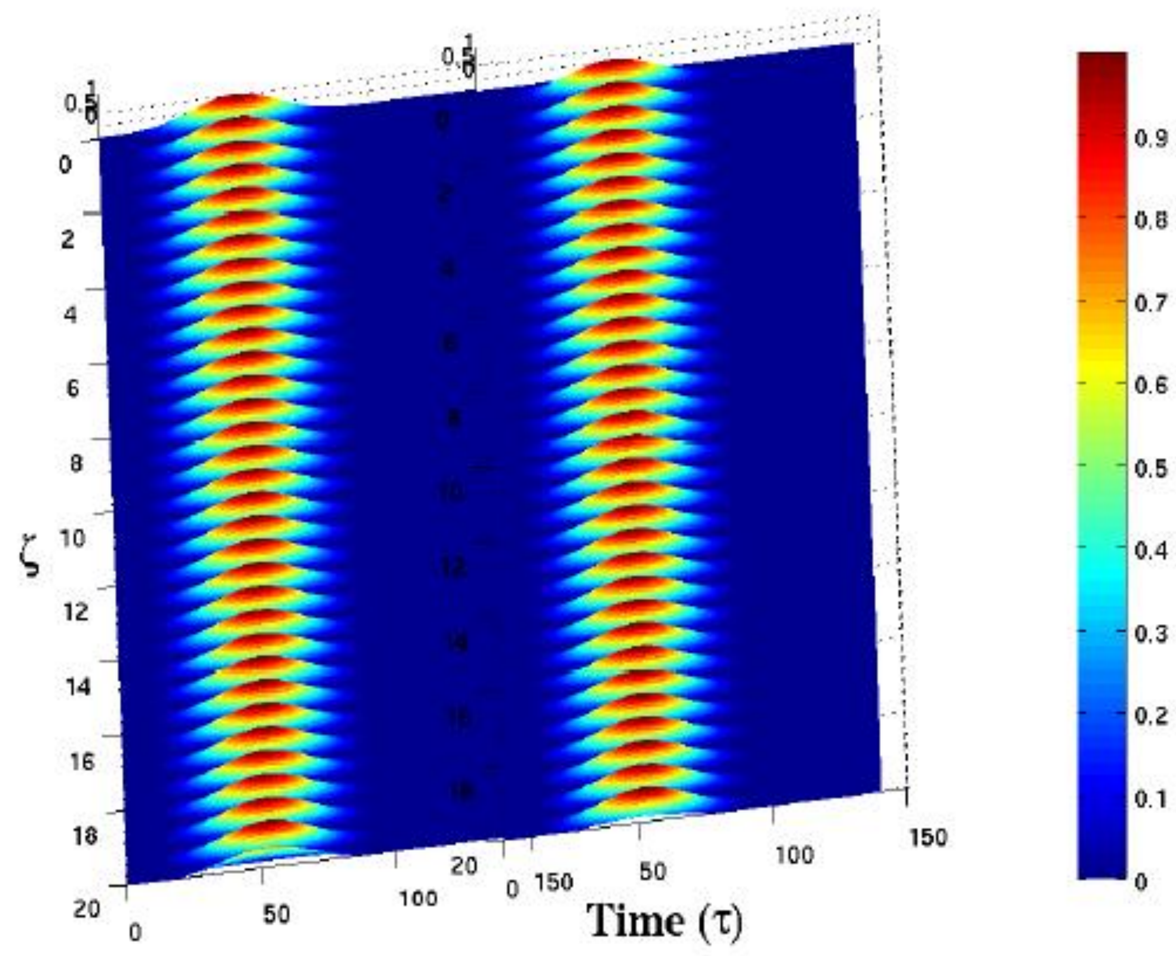

Figure 4: (Upper) The same as in Fig. 2 but with half the total pulse duration. This leads to weak non-adiabatic effects that change only the group velocity of the pulse. For the actual group velocity value see Eq. (13) of ref. [4]. By proper choice of the parameters slow light effects can be obtained.

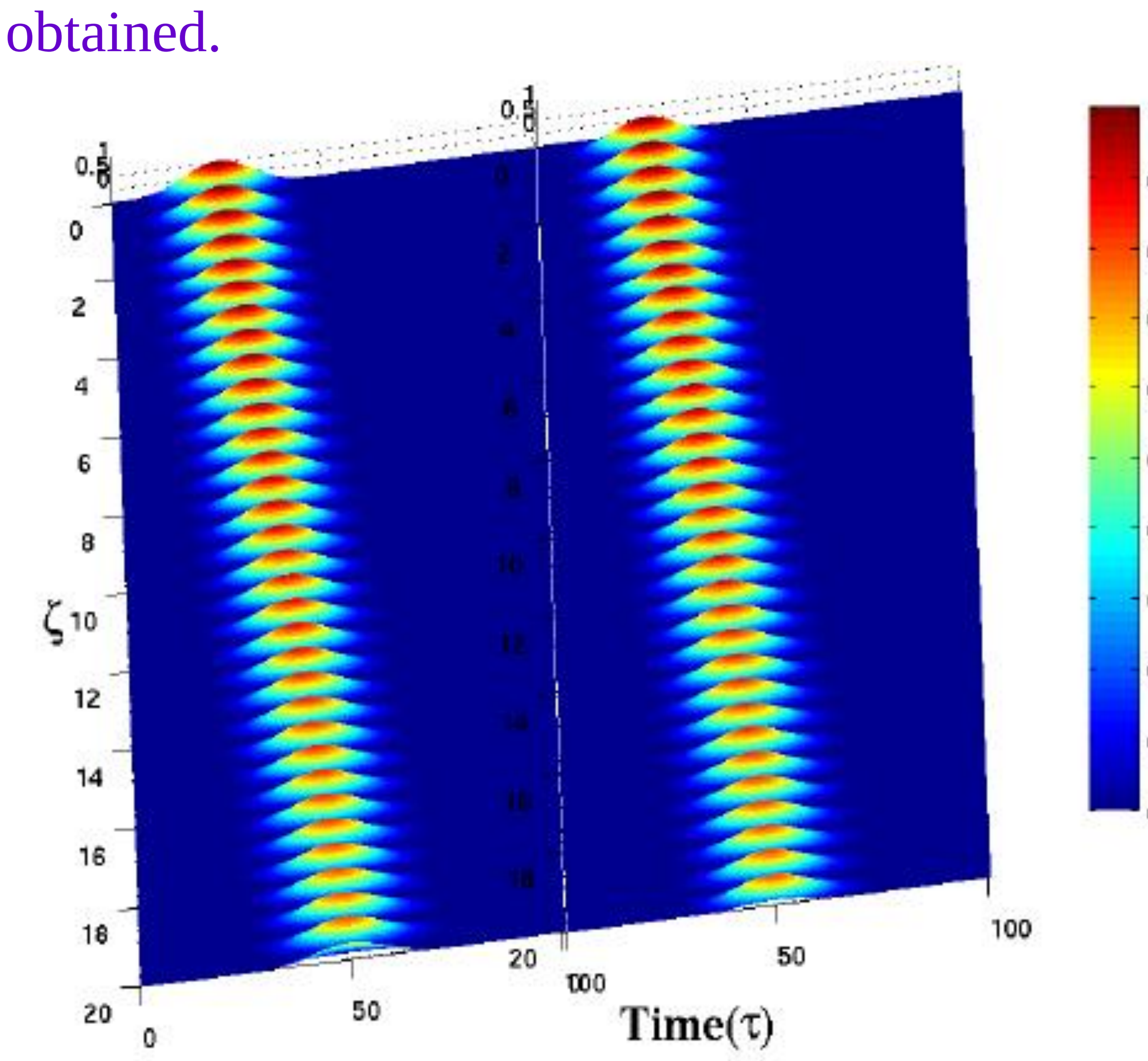

Figure 5: (Left) The same as in Fig. 2 but with one quarter the total pulse duration. This leads to strong non-adiabatic effects that both changes the group velocity of the pulse and also leads to absorption as the pulse propagates in the waveguides. Stronger non-adiabatic effects, that can be obtained for even shorter pulses, can additionally induce pulse shape distortion (not shown here).

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