Controlling all-optical switching in multicore nonlinear couplers

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Abstract

We demonstrate how to improve the switching power and performance of all-optical nonlinear couplers by introducing linear control waveguides. In particular, we demonstrate this idea for a three-core coupler consisting of an asymmetric Jensen's two-core nonlinear coupler weakly coupled to a linear control waveguide. We show that such a multicore coupler displays much better power switching behavior and is characterized by a much lower switching power in comparison with Jensen's coupler.

Keywords: Nonlinear optics; Nonlinear waveguides; Optical switching

1. Introduction

One of the most ambitious goals in nonlinear optics is the design of an all-optical computer that will allow the circumvention of the bottleneck that limits single-channel speeds in conventional (electronic) computers. Vital in this respect is the design of basic components such as all-optical routing switches and logic gates. Many of these devices employ a configuration of two parallel nonlinear waveguides in close proximity, which couple to each other through their evanescent fields. This allows the periodic exchange of power between the guides. This power transfer can be described accurately with the coupled-mode theory [1]. A first candidate switch was proposed by Jensen [2] in 1982, where the guides are made of a material with third-order optical susceptibility and the continuous wave (cw) limit is used. Jensen showed that when all the input power is initially launched into one of the guides, the nonlinear susceptibility can give rise to self-trapping of power in the original guide when the input power exceeds a certain threshold. As a consequence, the output power in the original guide changes from essentially 0% below threshold to nearly 100% above threshold, after a coupling length.

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Since the pioneering work of Jensen, several other coupler configurations have been considered. For instance, it was found that a three-in-a-line configuration of identical couplers in the cw limit display a more abrupt switching profile at the expense of greater input power [3]. Similar behavior was reported for a linear array of many identical couplers [4]. Along the years, most of the research have concentrated on pulse switching, where the coupled-mode equations are modified to take into account group-velocity dispersion [5] and dispersion of the coupling coefficient [6]. We continued however, examining new ways to optimize the switching profile of several nonlinear couplers, operating in the cw regime. The reason is that many features predicted for cw should also hold for pulse operation, in some parameters regime. For pulses, the system is characterized roughly by two competing length scales: the coupling length L_c, which is the shortest distance required for maximum power transfer between the guides and the 'walk-off' length L_w, which is the distance over which a significant portion of the original pulse breaks up. For instance, at picosecond pulses, or longer, the typical walk-off distance is of the order of tens of coupling lengths [6]. Thus, for a device length smaller than the walk-off distance, the cw operation should be a good approximation and the power transfer between the guides would resemble the switching phenomenon under cw conditions.

The single coupler is also of current interest due to several ways to increase the nonlinear response. For instance, in the so-called χ^2-couplers and switches, where the nonlinearity is of second order, in the weakly matched limit, this nonlinearity will resemble the χ^3 one. Since phase matching controls the efficiency of the effective nonlinearity, one may easily control linear versus nonlinear switching properties [7].

Thus, we have examined several coupler configurations for cw operation, aiming at optimizing their switching profile. First, we introduced [8] the doubly nonlinear trimer (DNT) coupler consisting of two nonlinear guides coupled to a third, linear guide in an isosceles-triangle configuration. Such system displays the interesting phenomenon of power self-trapping tunability: the critical input power level necessary for the onset of power self-trapping can be tuned to low values, by adjusting the value of the (linear) coupling between the nonlinear guides and the linear one [8,9]. In the optimal configuration, switching was achieved at one-fourth the power needed to produce switching in the Jensen coupler. The price to pay for this improved switching is the use of larger device lengths, up to 10 times that reported by Jensen, in addition to some rather strong oscillations in the transmittance profile [9]. We have also considered new hybrid models of nonlinear coherent couplers consisting of optical slab waveguides with various orders of nonlinearity [10]. The first model consisted of two guides with second-order instead of the usual third-order susceptibilities as typified by the Jensen coupler. This second-order system showed a power self-trapping transition at a critical power greater than that found in the third-order susceptibility coupler. Next, we considered a mixed coupler composed of a second-order guide coupled to a third-order guide and showed that, although it does not display a rigorous self-trapping transition, for a particular choice of parameters it does show a fairly abrupt trapping of power at a lower power than in the third-order coupler. By coupling this mixed nonlinear pair to a third, purely linear guide, the power trapping was brought to even lower levels. In this way a switching profile can be achieved at less than one sixth the input power needed in the Jensen coupler. The drawback is that the transmittance profile showed strong oscillations, in addition to a large coupling length [10].

In the present work we introduce a new coupler model, consisting of two homogeneous guides, with different (but constant) third-order susceptibility, weakly coupled to a third purely linear guide, introduced for controlling or 'tuning' purposes. It will be shown that the presence of this extra coupling together with the asymmetry in the nonlinearities, makes possible for the model to display an abrupt switching profile at low power levels (half of Jensen's or even smaller), without strong oscillations and with a reasonable coupling length (between 2.5 and 3 times of Jensen's, approximately).

2. A new coupler model

Consider a coupled system of two nonlinear guides, with third-order susceptibilities χ_1 and χ_2 respectively, and coupled to a third, purely linear guide (control guide). In the single-mode approximation and ignoring cross-phase modulation effects, the normalized mode amplitudes satisfy

$$
\begin{aligned}
\mathrm{i}\frac{\mathrm{d}C_1}{\mathrm{d}z} &= VC_2 + W_{13}C_3 - \chi_1|C_1|^2C_1, \\
\mathrm{i}\frac{\mathrm{d}C_2}{\mathrm{d}z} &= VC_1 + W_{23}C_3 - \chi_2|C_2|^2C_2, \qquad (1)\\
\mathrm{i}\frac{\mathrm{d}C_3}{\mathrm{d}z} &= W_{13}C_1 + W_{23}C_2,
\end{aligned}
$$

where $\chi_{1(2)} = Q_{1(2)}^{(3)}P$ is the product of an integral $Q_{1(2)}^{(3)}$ containing the third-order nonlinear susceptibility of guide 1(2) and the input power P, V is the linear coupling between guides 1 and 2 and $W_{13}(W_{23})$ is the coupling between the first (second) nonlinear guide and the linear guide. All the power is initially input into guide one, $C_1(0) = 1$, $C_2(0) = 0 = C_3(0)$. There are two conserved quantities in our system: The total normalized power $|C_1|^2 + |C_2|^2 + |C_3|^2 = 1$ and the total 'energy' $H = V(C_1C_2^* + C_1^*C_2) + W_{13}(C_1C_3^* + C_1^*C_3) + W_{23}(C_2C_3^* + C_2^*C_3) - (1/2)\chi_1|C_1|^4 - (1/2)\chi_2|C_2|^4 = -(1/2)\chi_1$. These quantities are useful to monitor the accuracy of the numerical computation. At this point it is interesting to note that system (1) possesses a useful symmetry that will simplify our subsequent work: All the $|C_i(z)|^2$ $(i = 1, 2, 3)$ are *invariant* under a change of sign in both, W_{13} and W_{23}. If we change $(W_{13}, W_{23}) \to (-W_{13}, -W_{23})$, then (1) is restored by the (unitary) transformation $(C_1, C_2, C_3) \to (C_1, C_2, -C_3)$.

In this work, we focus on three particular cases: (I) $W_{13} = W_{23} = W$ (triangular configuration), (II) $W_{13} = 0$, $W_{23} = W$ (linear right configuration) and (III) $W_{13} = W$, $W_{23} = 0$ (linear left configuration). These configurations are sketched in Fig. 1. We are interested in the transmittance of the array. This is defined as $|C_1(L_c)|^2$, where, for a given configuration, L_c is chosen as a length for which, $|C_1(L_c)|^2 = 0$ (or nearly zero), in the absence of nonlinearity (or power). Usually, but not always one chooses the smallest of the available L_c. For configuration I it can be proved that

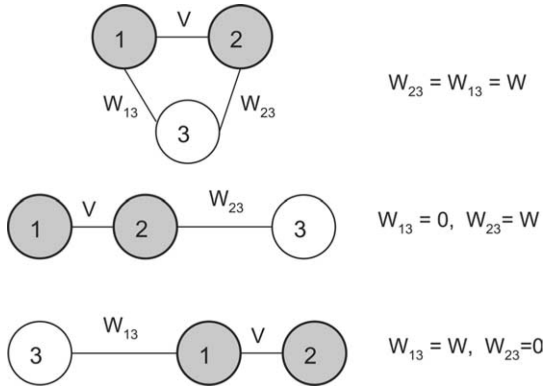

Fig. 1. New three-coupler configurations: 'triangular' (upper row), 'linear right' (middle) and 'linear left' (bottom). Couplers 1 and 2 possess third-order nonlinear susceptibilities $Q_1^{(3)}$ and $Q_2^{(3)}$, respectively, while coupler 3 (control guide) is purely linear.

there is no rigorous coupling length, regardless of the value of W, and one has to choose a convenient value from one of the minima of $|C_1(z)|^2$:

$$
\begin{aligned}
|C_1(z)|^2 = &\frac{V^2 + 4W^2}{4(V^2 + 8W^2)} + \frac{1}{4} + \left(\frac{\sqrt{V^2 + 8W^2} - V}{4\sqrt{V^2 + 8W^2}}\right) \\
&\times \cos\left[\left(\frac{3V - \sqrt{V^2 + 8W^2}}{2}\right)z\right] \\
&+ \left(\frac{\sqrt{V^2 + 8W^2} + V}{4\sqrt{V^2 + 8W^2}}\right) \\
&\times \cos\left[\left(\frac{3V + \sqrt{V^2 + 8W^2}}{2}\right)z\right] \\
&+ \frac{W^2}{V^2 + W^2}\cos(\sqrt{V^2 + 8W^2}z). \qquad (2)
\end{aligned}
$$

For configuration II, we find

$$
L_c^{\mathrm{II}} = \frac{\arccos(-(W/V)^2) + 2n\pi}{\sqrt{V^2 + W^2}} \quad (n = 0, 1, \ldots). \qquad (3)
$$

Thus, a rigorous L_c exists provided $|W/V| < 1$. Finally, for configuration III, we have

$$
L_c^{\mathrm{III}} = \frac{(2n + 1)(\pi/2)}{\sqrt{V^2 + W^2}} \quad (n = 0, 1, \ldots). \qquad (4)
$$

Next, we compute the transmittance numerically as a function of the input power P, sweeping over very many different values of χ_1, χ_2, for a fixed ratio W/V, generating a transmittance 'phase diagram' in χ_1, χ_2 space: Given a (χ_1, χ_2) pair, the value of the associated transmittance (a number between 0 and 1) is computed and displayed as a density plot. A low value of transmittance is marked by a dark dot, while higher values are marked with lighter levels of gray, all the way up to unit transmittance (white). In light of the above symmetry considerations, one needs only to consider positive ratios W/V, for a complete parameter space scan. Fig. 2 shows this phase diagram for the case $W = 0$, common to all three configurations. As power is increased we move on a straight line starting from the center with a slope determined by the ratio of χ_1 and χ_2. It is apparent from the phase diagram that while there are directions along which the transmittance rises quickly from zero, these do not lead to a particularly abrupt change in the transmittance, i.e., switching is not abrupt. In fact, it seems that Jensen's original candidate case $\chi_1 = \chi_2$ gives the best balance between abrupt switching and low power, for the $W = 0$ case.

Enter $W \neq 0$, i.e., a 'control' waveguide. Now the transmittance phase diagram is somewhat distorted, and the possibility arises of determining other 'good' directions, different from $\chi_1 = \chi_2$. The value of W can be varied simply by adjusting the relative distance between the nonlinear guides and guide 3. In fact, for each of the three configurations introduced at the beginning, we can find 'good' cases for switching. For instance, in Fig. 3 we show the case $W/V = 0.19$ for configuration I (triangular). Here, the 'good' direction $\chi_1 = 0.3\chi_2$ has been identified and leads to the transmission profile labelled in Fig. 4 as 'I'. Abrupt switching is

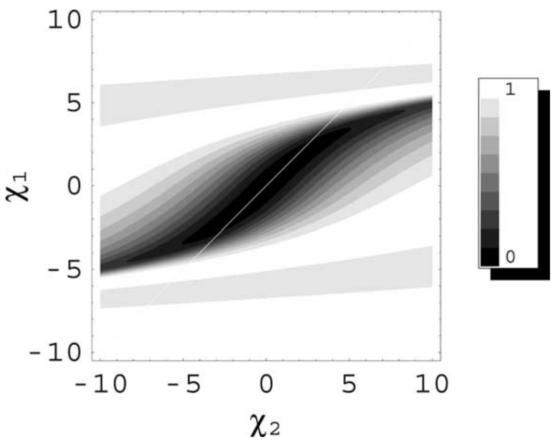

Fig. 2. Switching phase diagram in χ_1, χ_2 space, for the $W = 0$ case. For a given χ_1/χ_2 ratio, as power is increased the transmittance of the coupler can be visualized by moving along a straight line (with slope χ_2/χ_1) from the center. Dark (clear) regions denote low (high) values of the transmittance. The clear straight line denotes Jensen's candidate, $\chi_1 = \chi_2$.

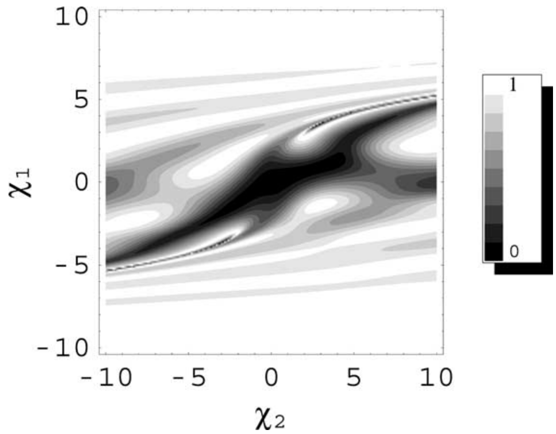

Fig. 3. Same as in Fig. 2, but for the 'triangular configuration' and $W/V = 0.19$, $L_c = 4.19/V$.

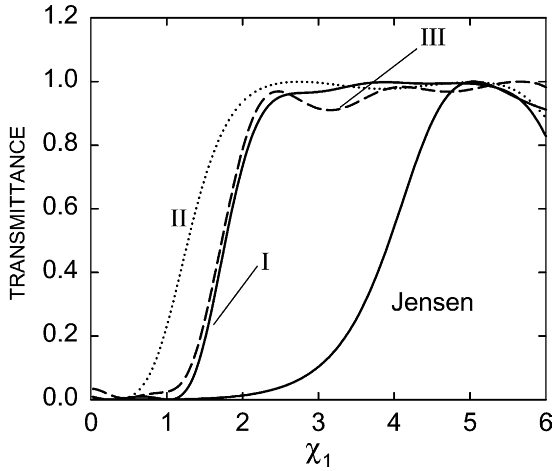

Fig. 4. Switching profiles for the three new coupler configurations proposed in this work. Solid line: 'triangular' configuration (I) with $W/V = 0.19$, $L_c = 4.19/V$ and $\chi_1/\chi_2 \approx 0.3$. Dotted line: configuration II, with $W/V = 0.3$, $L_c = 4.427/V$ and $\chi_1/\chi_2 \approx 0.298$. Dashed line: configuration III, with $W/V = 0.27$, $L_c = 4.27/V$ and $\chi_1/\chi_2 \approx 0.277$. Jensen's ($\chi_1 = \chi_2$ and $W = 0$) switching profile has also been included for comparison.

achieved at nearly one half the power level needed in Jensen's, with a reasonable coupling length, $L_c = 4.19/V$ and absence of strong oscillations. Other candidate cases, corresponding to configurations II and III are also shown in Fig. 4. For the case labelled 'II', $W/V = 0.3$, $L_c = 4.427/V$ and $\chi_1 = 0.297\chi_2$. For case 'III', $W/V = 0.27$, $L_c = 4.37/V$ and $\chi_1 = 0.277\chi_2$. Of all these cases, case 'I' remains the best, since it is devoid of significant oscillations for $\chi_1/V < 6$. It should also be mentioned that, for cases II and III the actual coupling lengths used differ a bit from the ones given by (3) and (4), since our primary objective is to achieve a sharp transmittance profile at as low power as possible. Thus, the use of an approximate L_c is acceptable, provided $|C_1(L_c)|^2$ remains small (see, for instance curve 'III' in Fig. 4).

3. Discussion

We have introduced and examined the switching properties of a new model of a nonlinear coherent coupler for cw operation: Two guides with different, but constant third-order nonlinear susceptibility, weakly perturbed, or 'controlled' by a third, purely linear guide. Power is initially launched on one of the nonlinear guides (guide 1). We focussed on three particular geometrical configurations: one, where the controlling guide is equally coupled to the nonlinear guides, another where the controlling guide is coupled to the guide 1 only, and finally the case where the controlling guide is coupled to guide 2 only. After a full sweep in parameter space (couplings and nonlinearities), we found 'good' values for W/V and χ_1/χ_2, that optimize switching for each of the three configurations. Of all of them, the 'triangular' configuration proved to be the best, displaying an abrupt switching profile at nearly a half power level than in Jensen's, with a reasonable coupling length and devoid of strong oscillations in the relevant power region. We conjecture that the reason for this improved performance hinges on the third (linear) guide, whose presence introduces another length scale into the system. By changing its coupling (distance) to the nonlinear coupler, we tune or 'control' the effective self-phase modulation (SPM) of the nonlinear coupler, responsible for power selftrapping. The decrease in power requirements for our optimized new coupler configuration also serves to decreases the possibility of two-photon absorption, which, of course, can be further minimized by working with frequencies below a half bandgap. Now, when considering pulses, one would expect that these results should still hold for pulse widths above picosecond levels, where the 'walk off' length [6] can be kept greater than the device's length. In this regard, the use of square-shaped pulse have proven convenient [11]. In conclusion, this significant improvement over Jensen's design we obtained, could constitute a strong candidate for a simple all-optical switch.

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