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All-optical switching of solitons in two- and three-core nonlinear fiber couplers

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We present a numerical investigation of all-optical switching of solitons in two- and three-core nonlinear fiber couplers. Both self-switching of solitons and phase-sensitive switching are considered. The extension of the results to multicore couplers is briefly discussed.

I. INTRODUCTION

In a recent theoretical paper Finlayson and Stegeman¹ have demonstrated that a three-waveguide nonlinear directional coupler offers some distinct advantages over and above the usual two-waveguide coupler as described by Jensen.² More generally, Christodoulides and Joseph³ have examined the stationary nonlinear solutions for an n -waveguide coupler, and Schmidt-Hattenberger *et al.*⁴ have investigated power-controlled switching (self-switching) between the output ports of multicore couplers. In particular, by comparison with the two-waveguide coupler n -waveguide couplers ($n > 2$) have more output states, markedly sharper switching characteristics, and display greater sensitivity to the input state, all of which are of central importance to proposed all-optical switching schemes.⁵ The price for this improved switching is, however, an increased switching power.¹

In this paper we report numerical studies of the propagation of short optical pulses in both two- and three-core nonlinear fiber couplers. These results are of significance since it is important to investigate how the projected advantages of using n -waveguide couplers (with $n > 2$) in the continuous wave (cw) limit manifest themselves when pulsed inputs are used.¹⁻⁴ In the absence of group velocity dispersion, the pulse breakup phenomena severely limits the switching capabilities of all the couplers.^{6,7} However, by using soliton input pulses in the anomalous group velocity dispersion (GVD) regime,^{8,9} it has been demonstrated numerically that efficient self-switching of whole pulses reminiscent of the cw results can be recovered for both nonlinear interferometers and switches.¹⁰⁻¹² Here we find that self-switching of solitons in a one-dimensional three-core array without excessive pulse breakup can be achieved, and with a sharper transmittance characteristic than the corresponding two-core case.¹ We also consider the case of phase-sensitive switching between the cores.¹³ Trillo and Wabnitz¹⁴ have recently investigated phase-controlled switching of solitons in a two-core fiber coupler. Here we show that a three-core coupler in triangular formation offers the best device characteristics, though the two-core coupler displays the sharpest phase-sensitive switching.

II. BASIC MODEL

We consider the three coupler configurations shown schematically in Figs. 1(a)–1(c), namely, two cores [Fig.

1(a)] and both a one-dimensional array of three cores [Fig. 1(b)] and three cores formed in an equilateral triangle [Fig. 1(c)] (In Fig. 1 and all the following figures a solid line is used to signify core 1, a dashed line for core 2, and a dotted line for core 3.) For the three-core array there is no interaction between cores 1 and 3 whereas they do interact in the triangular case. In all cases the cores are assumed identical and the evanescent field coupling between nearest-neighbor cores is therefore the same. Pulse propagation in the triangular three-core coupler [Fig. 1(c)] including the effects of GVD and self-phase modulation can then be described in terms of three linearly coupled nonlinear Schrödinger equations (NLSEs). If we denote the electric field envelopes in the three cores by a_1 , a_2 , and a_3 , and use soliton units,⁹ the coupled system of NLSEs can be written in a reference frame traveling at the common group velocity as

$$i \frac{\partial a_1}{\partial z} = -\frac{1}{2} \frac{\partial^2 a_1}{\partial t^2} - \kappa(a_2 + a_3) - |a_1|^2 a_1, \quad (1a)$$

$$i \frac{\partial a_2}{\partial z} = -\frac{1}{2} \frac{\partial^2 a_2}{\partial t^2} - \kappa(a_1 + a_3) - |a_2|^2 a_2, \quad (1b)$$

$$i \frac{\partial a_3}{\partial z} = -\frac{1}{2} \frac{\partial^2 a_3}{\partial t^2} - \kappa(a_1 + a_2) - |a_3|^2 a_3. \quad (1c)$$

Here κ is the linear coupling coefficient, and the equations are written assuming anomalous GVD and a positive nonlinearity. The corresponding equations for the two-core coupler [Fig. 1(a)] are obtained by setting $a_3 = 0$ in Eqs. (1a) and (1b) and the three-core array coupler [Fig. 1(b)] is described by setting $a_3 = 0$ in Eq. (1a) and $a_1 = 0$ in Eq. (1c). This system of linearly coupled NLSEs was solved numerically using the split-step method with up to 1024 temporal grid points.

III. RESULTS AND DISCUSSION

Figures 2(a)–2(c) shows the calculated transmittances as a function of the peak input power $P_{\max}$ corresponding to the couplers shown in Fig. 1. The calculations were performed with $\kappa = 1$, and the initial conditions $a_1(0, t) = \sqrt{P_{\max}} \text{sech}(t)$, $a_2(0, t) = a_3(0, t) = 0$. The transmittance of each core is calculated as the energy exiting that core divided by the energy injected into core 1. In each case a half-beat length coupler was considered with

FIG. 1. Schematics of the three fiber coupler configurations. (a) Two core coupler; (b) three-core coupler array; and (c) triangular three-core coupler. The continuous line corresponds to the incident core 1, and the dashed and dotted lines to cores 2 and 3, respectively.

the lengths calculated using (a) $L = \pi/2\kappa$, (b) $L = \pi/\sqrt{2}\kappa$, and (c) $L = \pi/3\kappa$. Figures 2(a) and 2(b) show the transmittance curves for soliton input pulses which are in correspondence to cw results of Finlayson and Stegeman.¹ Here it is clearly seen that even for soliton inputs the three-core coupler array [Fig. 2(b)] produces sharper switching between cores 1 and 3 than the two-core coupler [Fig. 2(a)] does between cores 1 and 2. Note, however, that for soliton inputs both couplers switch at about the same peak input power $P_{\max} \approx 4$, but the peak transmittance of the two-core coupler is higher in the bar state when the output is switched to core 1 (88% vs 76%). Examination of the transmitted pulse profiles shows that there is much more pulse breakup in the three-core coupler array compared to the two-core coupler. This illustrates that the theoretically demonstrated robustness of the soliton in a two-core coupler¹¹ falters as the number of cores is increased, as may be expected intuitively. The triangular three-core coupler [Fig. 2(c)] does not show sharp or pronounced switching. In this configuration the transmittances of cores 2 and 3 must be the same by symmetry and this limits the usefulness of the coupler in this mode of operation. Note, however, that the triangular three-core coupler has the shortest required length which is attractive from the device perspective.

Self-switching of solitons by varying the peak input power as depicted in Fig. 2 is only one possibility for all-optical switching. An alternative approach is to use phase-sensitive switching. Here the output port of a strong signal injected into core 1 is controlled by altering the phase of a weak signal applied to core 2. This has previously been demonstrated numerically in the cw regime including transverse effects,¹³ and for soliton pulses in a two-core half-beat length coupler.¹⁴ In both cases the basic concept is the same: In the absence of the weak signal the nonlinear coupler is prepared in an unstable state with the strong signal applied. From this unstable operating point the

FIG. 2. Core transmittances as a function of the peak input power $P_{\max}$ for a half-beat length (a) two-core coupler; (b) three-core coupler array; and (c) triangular three-core coupler. The powers shown on each plot are the unstable operating powers. The continuous line corresponds to the incident core 1, and the dashed and dotted lines to cores 2 and 3, respectively.

phase of the weak signal can be used to select the output port of the strong signal. In the cw case the unstable operating point for a two-core coupler is well known to be that input power (in core 1) for which the power in each core equalizes as a function of propagation distance.¹³ For the triangular three-core coupler the unstable operating point occurs when the power in all three cores equalizes. In Figs. 2(a) and 2(c) the corresponding peak input powers are found as those at which the transmittance curves cross, yielding $P_2 = 3.61$ and $P_3 = 4.84$. For the three-core cou-

pler array Fig. 2(b). shows there are several powers at which two of the transmittance curves can cross. Our numerical simulations show that in this case there are two potentially useful operating points corresponding to when the transmittance curves of cores 2 and 3 cross ($P_3^{(1)} = 3.24$), and when the transmittance curves of cores 1 and 2 cross ($P_3^{(2)} = 3.69$). Both of these operating points can be used for our purposes, but we shall concentrate on the case with peak input power $P_3^{(2)}$ since this yields the sharpest phase-sensitive switching characteristics.¹ Furthermore, our numerical simulations have shown that couplers much shorter than a beat length are relatively insensitive to the phase of the weak signal. This is clearly a consequence of the spatial mode instability which arises for couplers longer than a beat length.¹⁵ We therefore concentrate on the case of a beat length coupler.

Figures 3(a)–3(c) show the calculated transmittances as a function of the weak signal phase ϕ corresponding to the couplers in Fig. 1. The calculations were performed using $\kappa = 1$ and the initial conditions

$$a_1(t, z=0) = \sqrt{P_{\max}} \operatorname{sech}(t), \quad (2a)$$

$$a_2(t, z=0) = \sqrt{P_{\max}/100} \operatorname{sech}(t) \exp(i\phi), \quad (2b)$$

$$a_3(t, z=0) = 0. \quad (2c)$$

For each of the three couplers $P_{\max}$ was chosen as an unstable operating point as discussed above, and the transmittance was calculated as a function of ϕ . The two-core coupler displays a very sharp phase-sensitive switching behavior between the two cores as shown in Fig. 3(a), with a peak transmittance of $\approx 82\%$ when the output is switched to core 2. In contrast, the triangular three-core coupler does not show as sharp switching [Fig. 3(c)] but switching between all three cores with around 80% transmittance is possible: For $\phi = 0$ the output exits core 1, between $\phi \approx 36^\circ$ – 90° the output exits core 3, and between $\phi \approx 180^\circ$ – 240° the output exits core 2. This is a particularly attractive configuration since it requires the smallest device length. Figure 3(b) shows the transmittances of cores 1 and 3 for the three-core coupler array. Here sharp switching is seen for $\phi \approx 48^\circ$, but the overall switching characteristic is not very useful for device applications: When the output switches from core 1 to core 3 the peak transmittance is 72% and only occurs over a very small range of ϕ . Finlayson and Stegeman¹ have shown that the three-core coupler array can exhibit a chaotic response for long coupler lengths. In the cw regime chaos is predicted to occur for an input power corresponding to the point marked $P_3^{(2)}$ in Fig. 2(b) (see Figs 2 and 3 of Ref. 1). We therefore interpret the structures present in Fig. 3(b) as a signature of the chaos. However, since we are considering only a beat length coupler the system need not display a full blown chaotic response.

IV. SUMMARY AND CONCLUSIONS

In summary, we have presented a numerical investigation of both self-switching and phase-sensitive switching of solitons in two- and three-core nonlinear fiber couplers. As

FIG. 3. Core transmittances as a function of the weak signal phase ϕ for a beat length (a) two-core coupler, $P_2 = 3.61$; (b) three-core coupler array, $P_3^{(2)} = 3.69$, and (c) triangular three-core coupler, $P_3 = 4.84$. The continuous line corresponds to the incident core 1, and the dashed and dotted lines to cores 2 and 3, respectively.

in the cw regime, the three-core coupler array offers sharper transmittance characteristics for solitons compared to the two-core coupler.¹ However, for phase-sensitive switching the triangular three-core coupler offers the best device characteristics if one wants to take advantage of all three output ports. Finally, it is interesting to consider the extension of these results to even more cores ($n > 3$). Our numerical simulations show that in the three-core couplers the input solitons become far more distorted temporally than in the two-core case. In general, this causes the peak transmittance of any desired output core to decrease

as the number of cores is increased. Thus, as the number of cores increases the soliton ceases to display the particulate properties which lead to the whole pulse switching,¹⁰⁻¹² and the switching characteristics will eventually deteriorate in comparison to the two-core case.

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