Physica Scripta. Vol. 53, 582–585, 1996

Complementary Pairs of Dark and Bright Optical Pulses Obtained by Induced Switching at a Nonlinear Interface

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Received May 8, 1995; accepted September 1, 1995

Abstract

An experimentally simple scheme is proposed for obtaining complementary pairs of dark and bright pulses of adjustable width and contrast. The performance is based on a control-pulse disturbed total internal reflection of a probe beam at a nonlinear interface. The scheme seems attractive for generating of ultrashort dark/bright pulses in a broad range of wavelengths.

1. Introduction

In contrast to bright optical pulses, a dark pulse could be characterized as a localized intensity-dip against an uniform background. The dark/bright optical solitons form two specific classes of pulses, for which the group-velocity dispersion (GVD) is balanced by the medium nonlinearity [1, 2]. The generation of ultrashort dark optical pulses, however, seems more difficult compared to the generation of bright pulses. It is shown that continuous sinusoidal intensity modulation evolves into a train of dark solitons for normal GVD in the presence of a linear amplification [3]. Trains of dark solitons could be obtained also by a nonlinear propagation of visible pulses in optical fibers [4, 5]. Specially shaped, antisymmetric pulses, which closely correspond to the form of the fundamental dark soliton, are generated by spatial filtering within a temporally nondispersive lens and grating apparatus [6]. Recently, a scheme for a simultaneous pulse-shaping and shortening, as well as for the generation of special pulse forms was analyzed [7].

In this paper we propose an experimentally simple approach for generating complementary pairs of dark and bright optical pulses. The scheme proposed is based on a controllable switching of reflectivity and transmissivity at a nonlinear interface. The analyses are stimulated by the numerical results of Andersen and Regan [8] and by the experiment of Strobl and Golub [9].

2. Analysis of the interaction configuration

The nonlinear interface (NI) consists of a linear dielectric material in contact with an intensity dependent nonlinear material [9] and is illustrated in Fig. 1. Let us assume, that the linear medium has a refractive index n_0, whereas the nonlinear medium has a low-intensity refractive index $n_0 + \Delta n_1 (\Delta n_1 < 0;\ |\Delta n_1| \ll n_0)$. Two beams/pulses are involved in the scheme analyzed. The first beam called "control" propagates inside the nonlinear medium parallel to the NI. The second one, called "probe" is incident at an angle ψ less than the critical angle for total internal reflection (TIR). "Probe" means only that the behaviour of this wave will be analyzed in details. Generally, the nonlinear medium refractive index n_1 could be written as

$$n_1 = n_0 + \Delta n_1 - (1/2)n_2^c\,|A|^2 + (1/2)n_2^p\,|E_1|^2 \tag{1}$$

where A and E_1 are the electric field amplitudes of the control and probe beam/pulse, respectively, and $n_2^{c,p}$ denotes the respective nonlinear coefficient. The control beam/pulse self-action at $n_2^c > 0$ could disturb the TIR and, therefore, the probe beam/pulse could be partially transmitted by the NI. Once penetrated into the nonlinear layer, the probe beam/pulse could contribute (at $n_2^p > 0$) to this change of the NI-properties (see eq. 1). At $n_2^p < 0$, however, the penetrated wave would act as a limiter of the transmitted intensity [10]. The proper balance between the medium parameters and optical-wave intensities could lead to the reflection of a dark optical pulse with adjustable width and contrast and to the transmission of a complementary bright pulse. Let us concentrate our attention on the dark pulse reflected at the NI. It is convenient to introduce an effective, time-varying refractive index of the nonlinear medium

$$\Delta n_{1_{\rm eff}} = \Delta n_1 + (1/2)n_2^c\,|A|^2, \tag{2}$$

where the subscript "$1_{\rm eff}$" means effective low-intensity refractive index with respect to the probe field. In order to achieve an isolated dark optical pulse, the probe wave should be treated as CW or quasi-CW (forming an infinite background), whereas the control pulses should follow at a relatively low repetition rate. In the above notations, following the approach of Kaplan [11], the Snell's formula for the refractive angle ψ_1 has the form

$$(\psi + \psi_1)^2(\psi^2 + \Delta_{1_{\rm eff}}^{(2)} - \psi_1^2) + \psi^2\,\Delta_E^{(2)} = 0. \tag{3}$$

The Fresnel's formula for the amplitude reflectivity $r(|r| \leqslant 1)$ was derived in the form

$$6r\psi^2 + 4\Delta_{1_{\rm eff}}^{(2)}(1+r)^2 + \Delta_E^{(2)}(1+r)^4 = 0. \tag{4}$$

In eqs (3, 4) we used the notations

$$\Delta_{1_{\rm eff}}^{(2)} = 2\Delta n_{1_{\rm eff}}/n_0, \tag{5a}$$

$$\Delta_E^{(2)} = 4n_2^p\,|E_0|^2/n_0, \tag{5b}$$

whereas the relation between ψ, ψ_1 and r is described by

$$\psi_1 = \psi(1-r)/(1+r). \tag{5c}$$

Introducing the notations

$$D = \Delta_{1_{\rm eff}}^{(2)}/\psi^2, \tag{6a}$$

$$p = \Delta_E^{(2)}/\psi^2, \tag{6b}$$

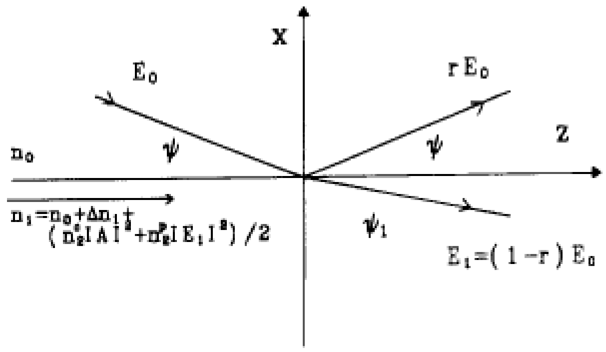

Fig. 1. Nonlinear interface configuration and interacting waves.

the Snell's [eq. (3)] and Fresnel's formula [eq. (4)] could be written, respectively, in the form

$$\{1 + (\psi_1/\psi)\}\{1 + D-(\psi_1/\psi)^2\} + P = 0, \tag{7a}$$

$$6r + 4D(1 + r)^2 + P(1 + r)^4 = 0. \tag{7b}$$

We plot the amplitude reflectivity r and the normalized refractive angle ψ_1/ψ *vs.* D in Figs 2 and 3, respectively. The dashed lines resulted from eq. (7b) and eq. (7a), respectively. The solid lines indicate existence of TIR ($r = 1$; $\psi_1 = 0$) and the switching from TIR to a partial transmission by the NI. In generating Figs 2, 3, $P = 4$ is assumed. It can be seen, that for a certain values of D two values of r ((ψ_1/ψ), respectively) are possible. According to the plane-wave theory [11] a hysteresis and bistability should exist. The analysis based on the Gaussian probe-beam approximation has shown, that no hysteresis should be expected [12]. Nevertheless, both approximations yield nearly equal reflection-transmission thresholds (see Fig. 7 in Ref. [12]). Initial experiments have shown a fast ("transient") hysteresis [12], but after improving the experimental setup no hysteresis has been found [13]. Later numerical simulations have indicated, that a remarkable improvement of the switching quality is possible by saturation of the nonlinearity [14, 15]. It should be pointed out that the results from Ref. [9–15] refer to the case when one intense laser beam is incident on the NI and reflection-to-transmission switching is caused by

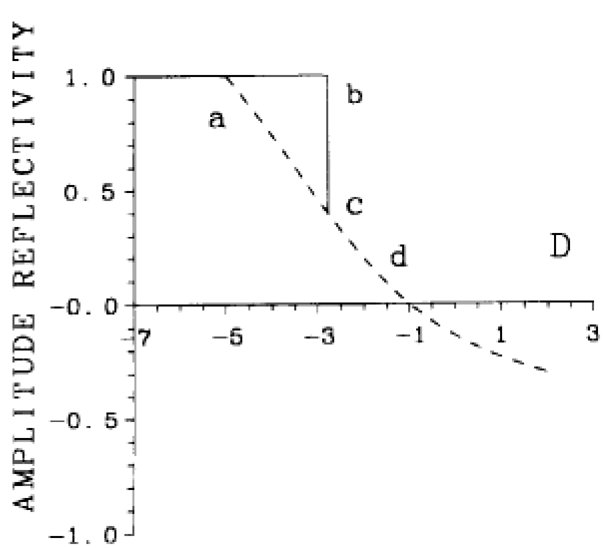

Fig. 2. Plot of the amplitude reflectivity r as a function of D. The dashed line is a result of eq. (7b). The solid lines indicate the exitence of TIR ($r = 1$) and the switching from TIR to a partial transmission (disturbed TIR).

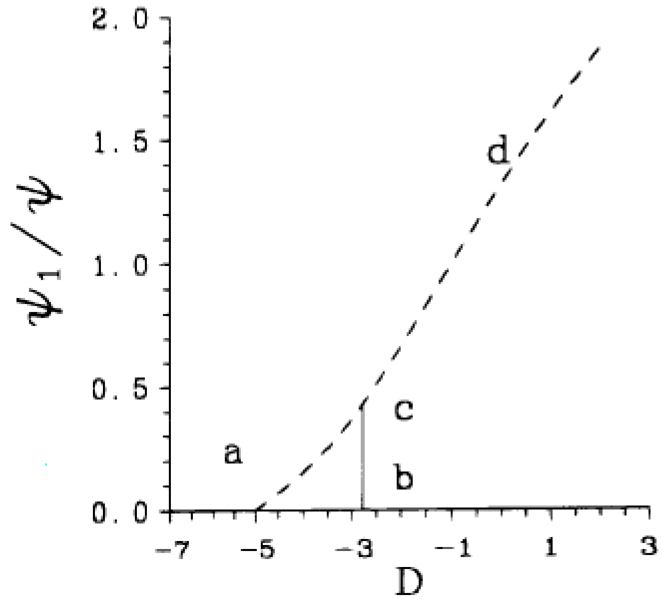

Fig. 3. Plot of the normalized refractive angle (ψ_1/ψ) as a function of D. The notations are the same as in Fig. 2.

the penetrating evanescent field into the nonlinear layer. Because of the presence of a control beam/pulse (more intense than the probe one), the configuration analyzed in this work is more complicated. We will assume, that no switching hysteresis exists.

3. Results and discussion

These results are obtained in a plane-wave approximation. Plane waves are unstable in self-focusing nonlinear media. The initiation of self-focusing, however, could be suppressed by an interferometric manipulation of the incident beams [16, 17]. In our opinion, a second way to overcome this problem also do exist. As shown in [10], the reflectivity of the NI does not depend strongly on the thickness of the nonlinear layer. Therefore, this layer could and should be thin enough to prevent probe-beam self-focusing inside. On the other hand, the useful length of the NI in our configuration is limited to the projection of the probe beam diameter on the interface, i.e. to

$$L_{NI} = 2\omega_0 \cot(\psi).$$

Therefore, reducing the probe beam radius ω_0, the control beam self-focusing distance f_{NL} [18] could appear to be much longer than L_{NI}. As a consequence, the collapse of the control beam should be prevented, too.

The most important feature of the NI used in this analysis is that a threshold value of the control-pulse intensity exists (i.e. a threshold value of D) at which the NI becomes partially transparent. At $D = D_{down}$ (points b, c on Fig. 2) a switching from TIR to partial transmission could be expected [11] and

$$D_{down} = -(P/2 + 1);\ P \in [0, 2)$$
$$\qquad -(2P)^{1/2};\ P \in [2, +\infty). \tag{8}$$

Under the assumption, that no hysteresis exists, the reverse switching should take place at $D_{up} = D_{down}$. In the opposite case, which is still an open question, the switching from a partial transmission to TIR should follow the dotted line of

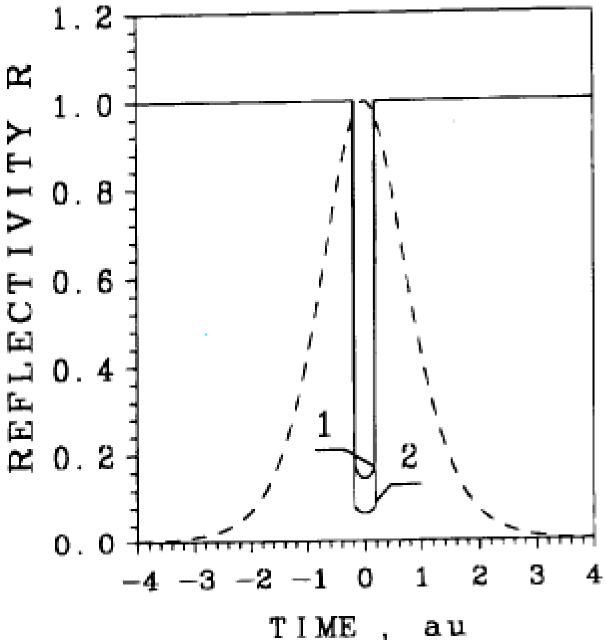

Fig. 4. Intensty reflectivity R of the nonlinear interface equal to the normalized dark pulse intensity (solid line) *vs.* time. Dotted curve – control pulse form-factor $f(\tau)$. Curve (1) – $P = 4$; $D_0 = -7$; $D = 4.3$; curve (2) – $P = 8$; $D_0 = -10$; $D = 6.1$.

Figs 2, 3 (Section c–a) and [11]

$$D_{up} = -(P + 1). \tag{9}$$

Let us assume that the nonlinearity is instantaneous and the control pulse is described by a form-factor

$$f(\tau) = \mathrm{sech}^2(\tau/\tau_0), \quad 0 \leqslant f(\tau) \leqslant 1. \tag{10}$$

Under the above assumptions time could be treated as a parameter. The normalized dark pulse intensity will reproduce the intensity reflection coefficient R of the NI. Introducing the notations

$$D_0 = 2|\Delta n_1|/(n_0\psi^2), \tag{11a}$$

$$D_1 = n_2^{\varepsilon}|A_0|^2/(n_0\psi^2), \tag{11b}$$

where $|A|^2 = |A_0|^2 f(\tau)$, one can separate the time-dependent term in D, i.e.

$$D = -D_0 + D_1 f(\tau). \tag{12}$$

Obviously, the maximum value of D is $D_{max} = -D_0 + D_1$. In order to achieve a switching at the NI, it is necessary to ensure two conditions, namely

$D_{max} > D_{down}$ – partial transmission in the peak of the control pulse;

$D_{min} < D_{up}$ – TIR in the leading and trailing wing.

If a dark pulse in the reflected wave and a complementary bright pulse in the refracted wave are desired, one should choose D_{max} above D_{down}.

The modulation depth will depend on the reflection $r(D_{down})$, i.e. on the parameter P [see eq. (8)]. Fig. 4 plots the dark pulses, obtainable in the reflected probe wave at $P = 4$ and $P = 8$ (the pulse of a higher contrast). Angle of incidence $\psi = 9.4^0$ and $\Delta n_1 = 0.1$ are assumed in the rest of this paper. It should be mentioned, that the values of P and D could be varied independently by the control- and probe intensities only. As seen, a higher value of P corresponds to a higher contrast dark pulse. For a reference, the dashed curve represents the control pulse form-factor $f(\tau)$. The relatively narrow dark pulse is a result of a high switching level, chosen to be near the control pulse peak-intensity. The dark pulse durations obtainable could not be less than the medium response time. If D_{max} is increased with respect to D_{down} [see eq. (8) and Figs 2, 3], the dark pulses tend to broaden monotonically. This tendency is presented in Fig. 5 for $P = 4$, $D_0 = -7$ and D ranging from 4.2 to 7.5. The double dark-peaked structure of curve (4) on Fig. 5 is a result of the sign-change or the amplitude reflectivity r (see Fig. 2) at large values of D. Of course this does not mean, that the intensity reflectivity changes its sign. This behaviour, in principle, indicates the possibility for obtaining pairs of dark pulses. In our view, this possibility does not seem to be of practical interest because of the slow change rate of r *vs.* D (the asymptotical part of D in Fig. 2 at $\lim_{D \to -\infty}[r(D)] = -1$).

Semiconductor-doped glasses fabricated using the laser evaporation method seem to be well suited for application in the analyzed scheme. It was shown, that CdTe-doped glass exhibits a third-order nonlinearity $\chi^{(3)}$ as high as $4 \cdot 10^{-7}$ esu with a response time of units of picoseconds [19]. For example, using a 10 ps control pulse, a control-to-probe peak-intensity ratio equal to 3, and $n_2^{\varepsilon} = 5 \cdot 10^{-7}$ esu, a control-pulse peak intensity of the order of $10^6\,\mathrm{W/cm^2}$ is required in order to achieve an induced switching at the NI.

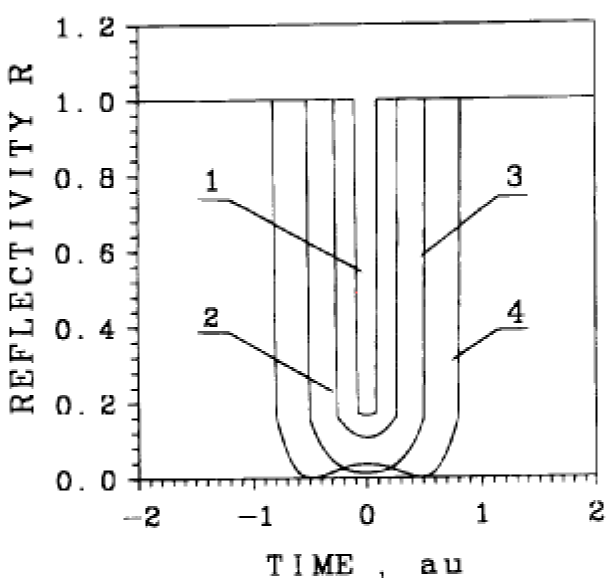

Fig. 5. Intensity reflectivity R of the nonlinear interface equal to the normalized dark-pulse intensity *vs.* time for $P = 4$ and $D_0 = -7$. Curve (1) – $D = 4.2$; (2) – $D = 4.8$; (3) – $D = 5.4$; (4) – $D = 7.5$.

4. Conclusion

We proposed an experimentally simple scheme for obtaining complementary pairs of rectangular dark and bright optical pulses of adjustable contrast and width (shorter than those of the control pulses). The performance is based on control-pulse disturbed total internal reflection of the incident probe beam at a nonlinear interface. The switching speed and the dark/bright-pulse fronts will be fundamentally limited by the response time of the nonlinear medium if no switching hysteresis exists. The latter one is still an open question requiring detailed numerical and experimental analyses. At a switching level near the peak of the control-pulse, the bright-pulse transmitted is expected to be well localized in space. Moreover, such a switching level will result in an increased temporal shortening of the complementary bright and dark pulses. The scheme proposed allows, in principle, starting from ultrashort laser pulses at a certain wavelength, pairs of bright and dark pulses of shorter width at different wavelengths to be obtained. Ultrafast all-optical beam deflection at a NI also seems feasible.

Acknowledgements

This work was done with the financial support of the National Fund "Young Scientist", Bulgaria, under a contract #MU-TT-1/1991.

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