All-optical switching by means of an interferometer with nonlinear frequency doubling mirrors

K. Koynov, S. Saltiel, and I. Buchvarov

University of Sofia, Faculty of Physics, Department of Quantum Electronics, 5 J. Bourchier Boulevard, 1164 Sofia, Bulgaria

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On the basis of theoretical consideration it is shown that a nonlinear frequency doubling mirror can be used as a lossless phase shifter. An interferometer that employs such nonlinear mirrors is suitable for all-optical switching and processing. © 1997 Optical Society of America [S0740-3224(97)01904-8]

1. INTRODUCTION

The nonlinear frequency-doubling mirror (NFDM) is a nonlinear (NL) optical device that consists of a mirror and a crystal for second-harmonic generation (SHG), separated by an adjustable distance from the mirror.[1] The NFDM has an intensity-dependent coefficient of reflection. It was demonstrated that this device can be used for mode locking of solid-state lasers in both pulsed[2–4] and cw modes[5–7] of operation, for pulse shortening,[8,9] as interactive negative feedback for obtaining an extremely long picosecond pulse train,[10] and as a nonreciprocal device.[11] In all these applications the process of SHG is exactly phase matched, and the fundamental and the second-harmonic (SH) waves do not experience NL phase shift.

Recently it was shown[12–14] that when a SH wave is generated in NL quadratic media slightly deviated from the exact phase-matched condition, the fundamental waves undergo an intensity-dependent NL phase shift. Both type I[12,13] and type II[14–16] interactions for SHG have been investigated. All-optical switching in a hybrid Mach–Zehnder interferometer with quadratic nonlinear media in one of the arms was reported recently.[17] An alternative all optical switching device, the frequency-doubling polarization interferometer, that also employs cascaded second-order processes is described in Ref. 18.

In this paper, on the basis of theoretical considerations, we show that the NFDM can be used as a phase-shifting element. As a design example for an all-optical switching device we propose a new type of NL interferometer–the Twyman–Green interferometer with a NFDM. The switching power of the new interferometer is four times lower than that of the nonlinear Mach–Zehnder interferometer described in the literature.[17]

2. NONLINEAR FREQUENCY-DOUBLING MIRROR AS PHASE SHIFTER

A schematic of the NFDM is shown in Fig. 1. The NL crystal is quasi-phase-matched for type I or type II SHG. The mirror M has maximum reflection for both fundamental and SH waves. The NL phase shift experienced by the fundamental waves is a result of a second-order cascading processes in the NL crystal[12–14] occurring during the first and the second passes of the waves through the crystal. The process of formation of the NL phase shift on the way back from mirror M is different from the process of formation of the NL phase shift on the way to the mirror because of the presence of strong seeding of the SH wave in the return pass. As shown in Refs. 19 and 20, when there is an input SH wave the fundamental NL phase shift is sensitive to the input phase difference between the SH and the fundamental waves. In this case the fundamental NL phase shift is due to two interactions[21]: a cubic one based on cascaded second-order processes and a single quadratic interaction with participation of the seeding wave.

The analysis of the NFDM as phase shifter is performed by solution of the reduced amplitude equations in the slowly varying approximation with assumption of zero absorption for all interacting waves:

$$\frac{dA_{1f}}{dz} = -i\sigma_1 \mathbf{A}_s \mathbf{A}_{2f}^* \exp(-i\Delta kz),$$

$$\frac{dA_{2f}}{dz} = -i\sigma_2 \mathbf{A}_s \mathbf{A}_{1f}^* \exp(-i\Delta kz),$$

$$\frac{dA_s}{dz} = -i\sigma_3 \mathbf{A}_{1f} \mathbf{A}_{2f} \exp(i\Delta kz), \tag{1}$$

where $\Delta k = k_s - k_{1f} - k_{2f} \neq 0$ and σ_i are NL coupling coefficients. Subscripts $1f$ and $2f$ refer to the fundamental waves, and subscript s refers to the SH wave.

System (1) is solved twice: first for the first pass through the crystal with zero amplitude for the generated wave and second for the return pass with input parameters—the result of the first solution of the system. The key factor for the return process is the relative phase difference $\Delta\varphi_{0,\text{in}} = \varphi_{1f} + \varphi_{2f} - \varphi_s$ at the entrance face of the NL crystal on the way back from the mirror. This is an additional degree of freedom that provides another way to control the resulting nonlinear phase shift.

System (1) is usually solved numerically,[12,13] by expressions that include Jacob integrals[15,22] that also have to be solved numerically, or by analytical expressions that are valid for low conversion coefficients.[21,23,24]

A. Analytical Approach

Analytical expressions obtained in the fixed-intensity approximation,[23] that allow one to describe the nonlinear phase shift (NPS) gained by the fundamental waves involved in type I or type II processes of SHG for the cases of zero and nonzero seeding for the generated wave were presented in Refs. 21 and 24.

For description of the NFDM we use the expressions for the amplitude and the phases of the interaction waves for $\mathbf{A}_s(0) \neq 0$, which are valid for the second pass of the fundamental waves through the crystal. The output at coordinate 0 (see Fig. 1) is

$$a_s^2(0) = \left[\frac{\sigma_3 a_{1f} a_{2f}}{\Lambda}\right]^2 \bigg\{ [4 + R^2 \Delta k^2 + 4R\Delta k \cos(\Delta\varphi_{0,\text{in}})] \sin^2\left(\frac{\Lambda L}{2}\right) + R^2\Lambda^2 \cos^2\left(\frac{\Lambda L}{2}\right) + 2R\Lambda \sin(\Delta\varphi_{0,\text{in}}) \sin(\Lambda L) \bigg\}, \tag{2}$$

$$\varphi_s(0) = \frac{\Delta k L}{2} + \varphi_{s,\text{in}}(L) - \arctan \frac{2\cos(\Delta\varphi_{0,\text{in}}) + R\Delta k}{2\sin(\Delta\varphi_{0,\text{in}}) + R\Lambda \cot(\Lambda L/2)}, \tag{3}$$

$$\varphi_{1f}(0) = \sigma_1\sigma_3 a_{2f}^2 V(\Delta\varphi_{0,\text{in}}) + \varphi_{1f}(L), \tag{4}$$

$$\varphi_{2f}(0) = \sigma_2\sigma_3 a_{1f}^2 V(\Delta\varphi_{0,\text{in}}) + \varphi_{2f}(L), \tag{5}$$

where

$$V(\Delta\varphi_{0,\text{in}}) = \frac{\Delta k L}{\Lambda^2} \bigg\{ [1 - SR^2 + R\Delta k \cos(\Delta\varphi_{0,\text{in}})] \times [1 - \text{sinc}(\Lambda L)] + R\Lambda \sin(\Delta\varphi_{0,\text{in}}) \times \left[\frac{1 - \cos(\Lambda L)}{\Lambda L} - \frac{\Lambda}{\Delta k}\cot(\Delta\varphi_{0,\text{in}})\right] \bigg\},$$

$$\Lambda = \sqrt{\Delta k^2 + 4S},$$

$$S = \sigma_3(\sigma_2 a_{1f}^2 + \sigma_1 a_{2f}^2),$$

$$R = \frac{a_s(L)}{\sigma_3 a_{1f} a_{2f}},$$

$$\Delta\varphi_{0,\text{in}} = \varphi_{1f,\text{in}}(L) + \varphi_{2f,\text{in}}(L) - \varphi_{s,\text{in}}(L) = \varphi_{1f,\text{out}}(L) + \varphi_{2f,\text{out}}(L) - \varphi_{s,\text{out}}(L) + \Delta\varphi_{\text{add}} + k_3 L - k_1 L - k_2 L.$$

In these expressions $a_s(L)$, $\varphi_{s,\text{out}}(L)$, $\varphi_{1f,\text{out}}(L)$, and $\varphi_{2f,\text{out}}(L)$ can be obtained from Eqs. (2)–(5), but when they are applied to the first pass through the crystal (entrance at $z = 0$ and output at $z = L$) and the seeding is zero, $R = 0$. The phases were corrected for the linear phase shift obtained in the distance between the crystal and the mirror and for the phase shifts that are result of the reflection from the mirror. Taking into account that

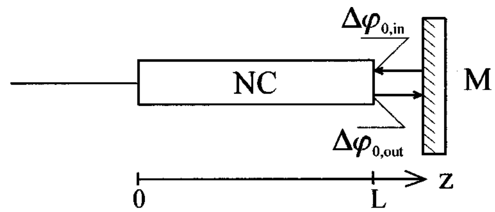

Fig. 1. Nonlinear frequency-doubling mirror (NFDM). NC, nonlinear crystal; M, mirror; for $\Delta\varphi_{0,\text{in}}$ and $\Delta\varphi_{0,\text{out}}$, see the text.

$$\Delta\varphi_{0,\text{in}}(L) = \Delta\varphi_{0,\text{out}}(L) + \Delta\varphi_{\text{add}} + \Delta k L \approx \Delta\varphi_{\text{add}} + \frac{\Delta k L}{2} + \frac{\pi}{2}$$

and with the condition that the mirror have maximum (100%) reflectivity for the fundamental and the second-harmonic waves, we obtain for the NPS of the reflected fundamental waves

$$\Delta\varphi_{1f,\text{NFDM}} = \sigma_1\sigma_3 a_{2f}^2 W(\Delta\varphi_{\text{add}}), \tag{6}$$

$$\Delta\varphi_{2f,\text{NFDM}} = \sigma_2\sigma_3 a_{1f}^2 W(\Delta\varphi_{\text{add}}), \tag{7}$$

where

$$W(\Delta\varphi_{\text{add}}) = \frac{\Delta k L}{\Lambda^2} \bigg\{ \bigg[2 - SL^2 \,\text{sinc}^2\left(\frac{\Lambda L}{2}\right) - \Delta k L \,\text{sinc}\left(\frac{\Lambda L}{2}\right) \sin\left(\Delta\varphi_{\text{add}} + \frac{\Delta k L}{2}\right) \bigg] \times [1 - \text{sinc}(\Lambda L)] + 2\sin\left(\frac{\Lambda L}{2}\right) \times \cos\left(\Delta\varphi_{\text{add}} + \frac{\Delta k L}{2}\right) \bigg[\frac{1 - \cos(\Lambda L)}{\Lambda L} + \frac{\Lambda}{\Delta k}\tan\left(\Delta\varphi_{\text{add}} + \frac{\Delta k L}{2}\right) \bigg] \bigg\}.$$

These expressions are valid only for low-input intensities for which conversion coefficients are less than 30%, corresponding to the restriction[21] $\sqrt{s}/\Delta k < 0.5$. It is difficult, at these values of the pump intensities and phase mismatches, to obtain values of NPS high enough for all-optical switching, but these analytical formulas can be used for analyzing the use of a NFDM as a quadratic Kerr-lens mode-locking device.[6,7] For analyzing a NFDM as the phase shifter at arbitrary pump intensities a numerical investigation of system (1) was performed.

B. Numerical Results

The system was solved numerically for the two cases in which (i) type I crystal and (ii) type II crystals for SHG are used as the frequency-doubling elements in the NFDM. In the first case one must have single fundamental-wave input, and in the second case two fundamental waves must be input with mutually perpendicular polarizations.

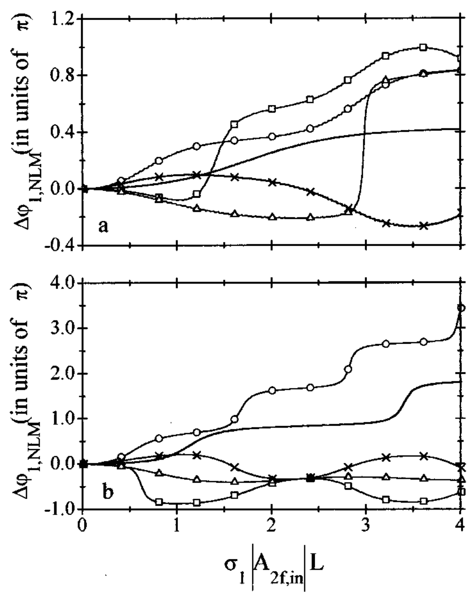

Fig. 2. Nonlinear phase shift as a function of the normalized input amplitude for different values of the additional phase shift $\Delta\varphi_{\rm add}$: circles, 0; crosses, $\pi/2$; triangles, π; squares, $3\pi/2$. Solid curve shows the case of a single-pass phase shifter. For all curves normalized mismatch is $\Delta kL = 1$. a, Type I crystal for SHG; b, type II crystal for SHG.

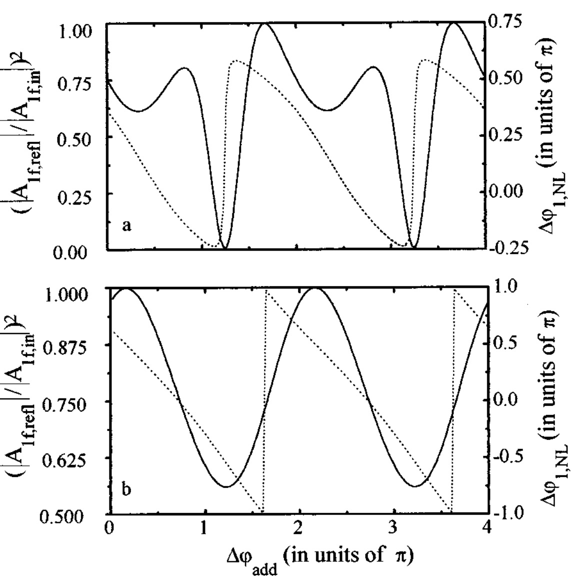

Fig. 3. Fundamental reflection (solid curve) and nonlinear phase shift (dotted curve) versus phase difference $\Delta\varphi_{\rm add}$. Normalized mismatch is $\Delta kL = 1$. a, Type I SHG; normalized input fundamental amplitude is $\sigma_1|A_{1f,\rm in}|L = 2$. b, Type II SHG; normalized input amplitude of the strong fundamental wave is $\sigma_1|A_{2f,\rm in}|L = 1$; the ratio of the two fundamental intensities is $(|A_{1f,\rm in}|/|A_{2f,\rm in}|)^2 = 0.1$.

As we have already noted, in the case of NFDM as a phase shifter it is possible to control the output nonlinear phase shift by altering the phases of the waves entering the crystal after reflection from the mirror. Figure 2 shows the output NPS for the reflected fundamental wave (for the case with a type II SH crystal—the weaker fundamental wave) for four different values of $\Delta\varphi_{\rm add}$: 0, $\pi/2$, π, and $(3\pi)/2$. For comparison we show the NPS after the first pass through the crystal $\Delta\varphi_{2f}(L)$. It is seen that NFDM is four times more effective as a phase shifter for low pump intensities and two times more effective as a phase shifter for higher levels of input intensities ($\sigma a_1 L > 2$). It is also seen from the figure that by adjustment of $\Delta\varphi_{\rm add}$ the sign of the induced phase shift can be changed.

Besides high NPS, another important property of NFDM is that, with slight deviation of $\Delta\varphi_{\rm add}$, total reflection of NFDM can always be obtained for the fundamental waves (no depletion). Figure 3a shows the reflection and the NL phase shift for the fundamental wave as a function of $\Delta\varphi_{\rm add}$ in the case of type I interaction and normalized input amplitude $\sigma_1|A_{1f,\rm in}|L = 2$ (where L is the length of the nonlinear media). The optimal value of $\Delta\varphi_{\rm add}$ for a $\pi/2$ NL phase shift and maximum reflection is

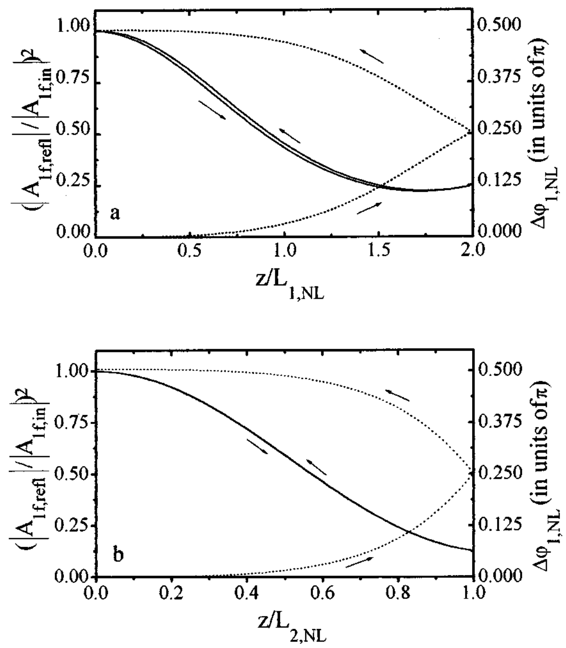

Fig. 4. Fundamental reflection (solid curve) and nonlinear phase shift (dotted curve) as a function of normalized propagation distance $z/L_{j,\rm NL}$, where $L_{j,\rm NL} = (\sigma_1 A_{jf,\rm in})^{-1}$. a, Type I SHG with optimal phase difference $\Delta\varphi_{\rm add} = 1.67\pi$. b, Type II SHG with optimal phase difference $\Delta\varphi_{\rm add} = 0.12\pi$. All other parameters are the same as for Fig. 3.

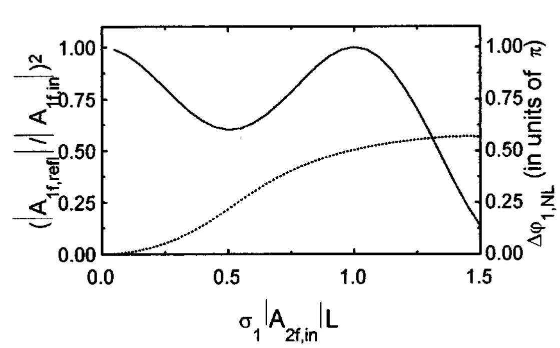

Fig. 5. Fundamental reflection (solid curve) and nonlinear phase shift (dotted curve) of the fundamental wave as a function of the normalized input amplitude $\sigma_1|A_{2f,\rm in}|L$ of the strong fundamental wave. Normalized mismatch is $\Delta kL = 1$ and $\Delta\varphi_{\rm add} = 0.12\pi$. Calculations are for type II SHG. The ratio of the fundamental intensities is $(|A_{1f,\rm in}|/|A_{2f,\rm in}|)^2 = 0.1$.

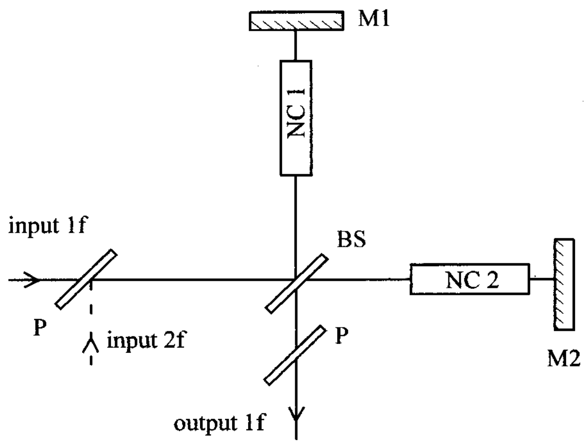

Fig. 6. Twyman–Green interferometer with NFDM. NC1, NC2, nonlinear crystals; M1, M2, mirrors; P, polarizers; BS, 50/50 beam splitter.

$\Delta \varphi_{\mathrm{add}} = 1.67\pi$. One easy way to adjust this optimal phase difference is to change the mirror–crystal distance. Similar dependencies for type II interaction are presented in Fig. 2b. In this case the necessary $\Delta \varphi_{\mathrm{add}}$ for simultaneously obtaining a $\pi/2$ NL phase shift and the maximum reflection of the weak fundamental wave ($1f$) was found to be 0.12π.

These figures show that, by proper adjustment of the phase difference $\Delta \varphi_{\mathrm{add}}$, 100% reflection of the fundamental wave in combination with an NL phase shift that is large enough for switching can be obtained. Figure 4 shows the growth of the NL phase shift and the reconstruction of the fundamental intensity inside the NL crystal. The required amplitude of the pump fundamental wave (or required length of the NL crystal) is at least twice as small in the case of NFDM use than in the case of one-pass phase shifters for the same type of SHG process, which corresponds to one-fourth the switching power for the interferometric all-optical switch with NFDM.

Additional advantages of the NFDM as a phase shifter in comparison with the single pass phase shifters are (i) that the birefringence transverse shift of the extraordinary beams is partially compensated in the return pass and (ii) the possibility of inserting a plate in the space between the crystal and the mirror to compensate for the temporal delay between the interacting pulses.

The curves in Figs. 2–4 were calculated with the assumption that the sign of the coupling coefficients σ_i is the same for both passes through the NL media. For some of the crystal media the sign of σ_i changes to the opposite on the way back from the mirror. For these crystals the optimal value of $\Delta \varphi_{\mathrm{add}}$ differs by π from the optimal value found for the case in which there is no change of sign. The fundamental NL phase shift and the reflection from NFDM are relatively insensitive to the length of the NL media and to the input amplitude (Fig. 5).

3. TWYMAN–GREEN INTERFEROMETER WITH NONLINEAR FREQUENCY-DOUBLING MIRROR

We propose that this phase shifting element be used for the construction of an all-optical switch based on a Twyman–Green interferometer (Fig. 6). The ordinary mirrors of a classical Twyman–Green interferometer are replaced by identical NFDM's. The interferometer can be modified in two ways. In the first the NFDM's employ type I interaction for SHG, and in the second, type II. These two modifications correspond to on–off and push–pull switching devices. The phase mismatches in both of the arms are opposite to each other, for example, $\Delta k' L = 1$ and $\Delta k'' L = -1$. Thus the NL phase shifts in both arms have opposite signs. A magnitude of $\pi/2$ for the NL phase shift will be sufficient for the interferometer switch. Normalized switching amplitudes at the input of the interferometer are 2.8 (for type I interactions) and 1.4 [for type II interactions, $(|\mathbf{A}_{1f,0}|/|\mathbf{A}_{2f,0}|)^2 = 0.1$]. The normalized amplitude 2.8 correspond to 700 MW/cm^2 if we choose a 1-cm-long LBO crystal for frequency doubling by a type I interaction. If we choose a 1-cm-long KTP crystal (suitable for type II interaction) for frequency doubling, the switching power will be 50 MW/cm^2.

4. CONCLUSION

In conclusion, we have shown that NFDM can be used as an effective phase shifter. The magnitude and the sign of the obtained nonlinear phase shift can be controlled by the value of the phase shift collected by the waves in the space between the mirror and the crystal. Here we propose a new type of nonlinear optical interferometer with nonlinear frequency doubling mirrors. In addition to all-optical switching, a modification of this new nonlinear optical interferometer can be used for measurement of the value of $\chi^{(2)}$ of the media used for frequency doubling, as for the Twyman–Green interferometer with phase conjugation mirrors used for measurement of $\chi^{(3)}$.[25–27]

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Authors may be reached by fax at 359 2 96 25 276 or by e-mail at saltiel@phys.uni-sofia.bg

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