Nonlinear adiabatic optical isolator

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We theoretically propose a method for optical isolation based on adiabatic nonlinear sum frequency generation in a chirped quasi-phase-matching crystal with strong absorption at the generated sum frequency wave. The method does not suffer from limitations of dynamic reciprocity found in other nonlinear optical isolation methods, and can provide tunable optical isolation with ultrafast all-optical switching capability. Moreover, as an adiabatic technique it is robust to variations in the optical design and is relatively broadband. © 2018

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An optical isolator (optical diode) is the optical correspondent of electronic diode, allowing unidirectional non-reciprocal light transmission. These devices are widely used in optical telecommunications and laser applications to prevent the unwanted feedback that might be harmful to optical instruments and devices. Moreover, the use of an isolator generally improves the performance of an optical circuit as it suppresses spurious interferences, interactions between different devices and undesired light routing [1]. Currently, optical diodes rely almost exclusively on the Faraday effect where external magnetic fields are used to break time reversal symmetry [2]. However, optical isolators based on the Faraday effect are typically large-size devices, they cannot be implemented easily in on-chip integrated systems [3], and do not provide dynamic optical isolation with all-optical switching capability, which is desirable in advanced optical signal processing.

Several recent works have suggested and experimentally demonstrated new ways to realize optical isolators that do not rely on magneto-optical effects [4–19]. Dynamic modulation methods, which enable tunable optical isolation with all-optical switching capabilities, have been recently proposed and experimentally demonstrated using liquid-crystal heterojunctions [7], phase modulators in InP and silicon photonics [9, 10], opto-acoustic photonic crystal fibers [11], and traveling-wave Mach-Zehnder modulators [12]. A broad class of optical isolators is the one based on nonlinear interaction of light in a nonlinear medium, which breaks Lorentz reciprocity. Nonlinear optical isolators have raised great attention since more than two decades [4–6, 13–19], mainly because of their all-optical switching capability exploiting the ultrafast response of the nonlinear medium and for on-chip integration possibilities. However, their effectiveness in optical isolation has been recently questioned owing to the appearance of so-called dynamical reciprocity [20]. In a nonlinear optical isolator, non-reciprocal transmission contrast is observed when strong waves are injected in forward or backward directions, however optical isolation is constrained by a reciprocity relation for a class of small-amplitude additional waves that can be transmitted.

In this Letter we suggest a different route toward nonlinear optical isolation, which does not suffer from dynamical reciprocity limitations. The method is based on three wave mixing process in a second-order nonlinear medium with a strong control pump wave at frequency $\omega_1$, a weak signal wave at frequency $\omega_2$, and large absorption at the generated frequency $\omega_3 = \omega_1 \pm \omega_2$. The undepleted pump approximation linearizes the three wave mixing process and thus our nonlinear optical diode does not suffer from dynamical reciprocity. Furthermore since the nonlinear response of the medium is very fast (instantaneous), switching on and off the pump wave results in on/off diode action, allowing for ultrafast all-optical switching isolation capability. Finally to make the optical diode robust and relatively broadband we use adiabatic frequency conversion in aperiodically-poled quasi-phase-matched (QPM) crystals, a technique recently demonstrated by Suchowski et al. [21–25]. The feasibility of the method is illustrated for sum frequency generation in potassium titanyl phosphate (KTP) crystals, showing the possibility of achieving an optical isolation up to $\sim 40$ dB over more than 50 nm in the near-infrared.

The starting point of our analysis is provided by a standard model of sum frequency generation (SFG) or frequency difference generation (DFG) in a nonlinear second-order crystal with a chirped QPM grating, in which the SFG (or DFG) wave experiences strong linear absorption during propagation along the crystal. For the sake of definiteness, we will consider here the SFG case, however a similar analysis holds for the DFG scheme. In the undepleted pump approximation, SFG is described by the linear coupled equations [26, 27]

$$i \frac{d}{dx} \tilde{A}_2 = \frac{1}{2} \Omega_2 \tilde{A}_3 \exp \left(-i \int_0^x \Delta k(\xi) d\xi \right), \quad (1a)$$

$$i \frac{d}{dx} \tilde{A}_3 = \frac{1}{2} \Omega_3 \tilde{A}_2 \exp \left(i \int_0^x \Delta k(\xi) d\xi \right) - i \Gamma \tilde{A}_3 (1b)$$
Fig. 1. (Color online) Principle of a nonlinear adiabatic optical diode. Adiabatic SFG schemes with no absorption at the generated frequency (a) and with absorption at the generated frequency (b) and (c). (a) Slowly changing the coupling period along the crystal length ensures broadband and robust generation of the SFG wave. (b) For a forward propagating signal wave, the broadband SFG wave is absorbed in the crystal, and no transmission occurs. (c) Reversing the propagation direction of the signal breaks the symmetry and as a result there is no interaction of the contra propagating pump and signal waves. Therefore (b) together with (c) work as a broadband optical diode.

where $\tilde{A}_2$, $\tilde{A}_3$ are the slowly-varying amplitudes of signal and SFG waves at frequencies $\omega_2$ and $\omega_3 = \omega_1 + \omega_2$, respectively, $\omega_1$ is the frequency of the pump beam with undepleted amplitude $\tilde{A}_1$, $\Delta k(x)$ is the effective residual local phase mismatch that accounts for the chirped QPM grating, $\Omega_m = \chi^{(2)}\omega_mA_1/(2cn_{\omega_m})$ are the coupling coefficients, $n_{\omega_l}$ ($l = 1, 2, 3$) is the refractive indices of the crystal at frequency $\omega_l$ ($l = 1, 2, 3$), $\chi^{(2)}$ is the effective second order susceptibility of the crystal, $x$ is the position along the propagation axis, $c$ is the speed of light in vacuum, and $\Gamma$ is the absorption coefficient of the SFG wave. After the substitution $\tilde{A}_2 = A_2\sqrt{\Omega_2}\exp\left[-i\int_0^x d\xi\Delta k(\xi)/2\right]$, $\tilde{A}_3 = A_3\sqrt{\Omega_3}\exp\left[i\int_0^x d\xi\Delta k(\xi)/2\right]$ Eq. (1) can be cast in the form

$$\frac{d}{dx}\begin{pmatrix} A_2 \\ A_3 \end{pmatrix} = \frac{1}{2}\begin{pmatrix} \Omega & \Delta k - i\Gamma/2 \\ \Delta k & \Omega \end{pmatrix} \begin{pmatrix} A_2 \\ A_3 \end{pmatrix},$$

where $\Omega = \sqrt{\Omega_2\Omega_3}$. Interestingly, Eq. (2) can be viewed as a photonic analogue of a two-level atomic system which interacts with an external chirped pulsed field, with the excited state decaying out of the system with a decay rate $\Gamma$ [28–30]. For a linear chirp $\Delta k(x) = ax$, Eq. (2) describes the dissipative Landau-Zener model which admits of an exact solution in terms of parabolic cylinder functions [29]. The non-vanishing absorption $\Gamma$ at the SFG wave basically annihilates the signal wave while being converted in the nonlinear crystal, thus preventing forward propagation, while the chirped QPM grating ensures broadband and robust optical isolation under adiabatic operation. The limiting case $\Gamma = 0$, previously considered in Refs. [21, 22, 26], realizes broadband SFG via adiabatic rapid passage under the adiabatic condition

$$\left|\frac{\Omega}{d/dx}\Delta k\right| \ll (\Omega^2 + \Delta k^2)^{3/2}.$$ (3)

Such a condition requires a smooth $x$ variation of the phase mismatch $\Delta k(x)$, i.e. a sufficiently small gradient $\alpha$, and large coupling $\Omega$. In this way broadband, robust and almost $\sim 100\%$ conversion efficiency of the injected signal wave into the SFG wave can be obtained; see Fig. 1(a). To realize an optical diode, a relatively strong absorption at the generated SFG wave should be considered. Absorption together with the pump field direction break mirror symmetry and the optical transmission of the signal wave at frequency $\omega_2$ becomes non-reciprocal, as schematically shown in Figs. 1(b) and (c). In fact, in the forward propagation direction phase matching among signal, pump and SFG wave is realized, the signal wave is converted into the SFG via rapid adiabatic passage and the SFG is fully absorbed [Fig. 1(b)]. On the other hand, for backward propagation of the signal wave the phase matching for frequency conversion is not realized and the crystal turns out to fully transmit the signal wave [Fig. 1(c)]. To realize the nonlinear optical diode, some constraints should be met for the absorption coefficient, crystal length and adiabatic rate of the QPM grating in order to satisfy the adiabatic condition (3) and to avoid the so-called overdamping problem, i.e. phase mismatch induced by too strong absorption. Such constraints were investigated in details in the study of the dissipative Landau-Zener model [28, 29]. In addition to the adiabatic condition (3) the absorption coefficient should be strong enough at the generated SFG wave in order to suppress it, but too strong absorption coefficient will have opposite effect as pointed by Vitanov and Stenholm [29]: a too strong absorption freezes the dynamics like in an overdamped oscillator. One can view the effect of the large absorption rate as similar to that of large phase mismatching: both effectively decouple the interaction in three wave mixing. The optimum regime for the optical diode is realized when the absorption rate is of the same order as the coupling, i.e. $\Gamma \approx \Omega$ [29].

To illustrate the feasibility of the proposed method and to provide design-parameter of optimized optical isolation based on the photonic analogue of the dissipative Landau-Zener model, let us consider SFG in potassium titanyl phosphate KTiOPO$_4$ (KTP) crystal. KTP crystals are commonly used in nonlinear optics applications, showing high damage threshold, a high nonlinear optical coefficient and strong absorption in the near ultraviolet spectral range [31, 32]. In waveguide configuration, relatively long crystals can be manufactured with small mode area to ensure high intensity and diffraction-free long interaction lengths [33, 34]. We consider specifically type-0 SFG at room temperature, with a strong pump
Fig. 2. (Color online) Schematic of the nonlinear adiabatic optical diode realized in a KTP waveguide with a linearly-chirped QPM grating. The strong pump wave at frequency $\omega_1$ and the weak signal wave at frequency $\omega_2$ are polarized in $z$ direction and phase matched in the KTP crystal to generate the SFG wave at frequency $\omega_3 = \omega_1 + \omega_2$, which is strongly absorbed by the crystal.

Fig. 3. (Color online) Numerically-computed isolation spectra of the nonlinear adiabatic isolator for three different pump intensities $I_1 = 200, 300$ and $500$ MW/cm$^2$ versus wavelength of the signal wave for a 5-cm-long KTP crystal. The isolation of a 5-cm-long phase-matched crystal at 930 nm signal with constant poling period of 1.79 $\mu$m is plotted by black dashed-dotted curve for easy reference.

Pump wave at wavelength $\lambda_1 = 532$ nm and a weak signal wave at around $\lambda_2 = 930$ nm, corresponding to a SFG wave at $\lambda_3 = 338$ nm. The optical waves propagate along the $x$ optical axis and all electric fields are polarized in $z$ direction of the crystal (Fig.2), while phase matching over a bandwidth of more than 50 nm is achieved using a linearly-chirped QPM grating. The absorption coefficient of KTP at the SFG wave $\lambda_3 \sim 340$ nm is $\Gamma \sim 229$ cm$^{-1}$ [35]. In our simulations, we assume a strong pump wave at $\lambda_1 = 532$ nm with an intensity $I_1$ up to 300-500 MW/cm$^2$, which provides high efficiency frequency conversion avoiding the overdamping problem discussed above. For a KTP waveguide with an effective mode area $A_1 \sim 10$ $\mu$m$^2$, a pump intensity of 300 MW/cm$^2$ corresponds to an optical pump power $P_1 = A_1 I_1 \sim 30$ W, which is available both in continuous-wave or pulsed regimes from frequency-doubled high-power Nd:YAG lasers [36]. A crystal length of 3-5 cm is typically assumed, with poling period of the chirped grating varying from 1.7 $\mu$m to 1.9 $\mu$m along the sample for first-order QPM. Such grating periods are feasible with current poling techniques in KTP [37]. The performance of the nonlinear optical diode is provided by the isolation parameter, defined as

$$dB = 10 \times \log_{10} \left( \frac{T_f}{T_b} \right),$$

where $T_f$ and $T_b$ are the transmitted electric field intensities in the forward and backward directions, respectively. Figures 3 and 4 show the numerically-computed isolation parameter of the adiabatic nonlinear diode for 5-cm and 3-cm-long KTP crystals, respectively. As can be seen from the figure, a maximum isolation of $\sim 40$ dB and good isolation $>35$dB over a spectral region of 60 can be obtained in the longer crystal configuration.

In conclusion, we have presented a novel route toward the realization of broadband and tunable nonlinear optical isolators with ultrafast all-optical switching capabilities, that do not suffer from dynamical reciprocity commonly found in nonlinear optical isolation schemes [20]. Our method is based on adiabatic frequency conversion (SFG) in aperiodically-poled quasi-phase-matched crystals with strong absorption at the generated SFG wave. Ultrafast tunability of optical isolation can be simply achieved by changing the intensity level of the strong pump wave. Frequency
 conversion in the chirped nonlinear crystal is described by an effective dissipative Landau-Zener model [28–30], efficient frequency conversion and absorption of the SFG wave requiring a balance between absorption coefficient and nonlinear coupling. The feasibility of the method has been discussed by considering as an example optical isolation in the near-infrared (∼900 nm) using a KTP crystal with a chirped QPM grating pumped at 532 nm (frequency-doubled Nd:YAG laser). Optical isolation up to ∼40 dB over more that 50 nm bandwidth has been obtained in numerical simulations. Such a relatively strong and broadband optical isolation indicates that nonlinear optical schemes can provide viable routes toward tunable optical isolation with ultrafast switching capabilities, without being limited by dynamical reciprocity [20].

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