All-optical diode action in asymmetric nonlinear photonic multilayers with perfect transmission resonances

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Light propagation in asymmetric Kerr-nonlinear multilayers with perfect transmission resonances is theoretically investigated. It is found that hybrid Fabry-Perot-resonator–photonic-crystal structures of the type $(BA)^k(AB)^k(AABB)^m$ exhibit both pronounced unidirectionality (due to strong spatial asymmetry of the resonant mode) and high transmission (due to the existence of a perfect transmission resonance). This results in nonlinear optical diode action with low reflection losses without need for a pumping beam or input pulse modulation. By slightly perturbing the perfect transmission resonance condition, the operating regime of the optical diode can be tuned, with a tradeoff between minimizing the reflection losses and maximizing the frequency bandwidth where unidirectional transmission exists. Optical diode action is demonstrated in direct numerical simulation, showing >92% transmittance in one direction and about 22% in the other. The effect of perfect transmission resonance restoration induced by nonlinearity was observed analytically and numerically. The proposed geometry is shown to have advantages over previously reported designs based on photonic quasicrystals.

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I. INTRODUCTION

An optical device capable of unidirectional light transmission (an *optical diode*) is a direct analogy to an electronic diode and has great application potential in optical communication and information processing. To this end, a variety of effects can be used, including magnetooptical [1–3], liquid-crystal [4], nonlinear [5–9], or gyroanisotropic [10] elements in photonic microstructures. Also, several new concepts have been proposed recently such as indirect photonic interband transitions [11], planar chiral [12,13], or negative-refraction [14] metamaterials. Among all these approaches, nonlinear one-dimensional (1D) photonic multilayers deserve special attention because of their extreme simplicity in fabrication and modeling. This allows us to explore the optical properties of nonperiodic structures systematically and in a wide range of geometries (see, e.g., [15]). In addition, a potential for versatile ultrafast pulse control by multilayer structures only a few micrometers thick has been shown in recent experiments [16,17].

The operation of a nonlinear photonic multilayer-based optical diode relies on two principles. First, the structure should be strongly *nonlinear*. A spectral resonance is usually employed to enhance the nonlinear interaction, also providing the structure with a highly transmissive state which is very sensitive to parameter variations. Second, the structure must be spatially *asymmetric* so that the resonant mode couples more strongly to the wave impinging from one side (e.g., from the left) than from the other side. This causes a direction-dependent refractive index change due to the Kerr nonlinearity. So, the leftward-impinging wave can induce a sufficient shift in the resonant frequency ω_{res} so that it matches the incident wave frequency ω_0, resulting in a high left-to-right transmission, while the rightward-impinging wave causes a weaker shift

of ω_{res} so that $\omega_{res} \neq \omega_0$, resulting in a lower right-to-left transmission. Several design ideas have been proposed, achieving spatial asymmetry using a graded refractive index [5,6] or asymmetrically placed defects [7,8,14] in a 1D photonic crystal (PhC), or, more recently, using inherently asymmetric eigenstates in photonic quasicrystals [9]. Generalizations of the approach beyond the 1D multilayer geometry have also been reported, based on quasi-1D coupled-resonator [18,19] or two-dimensional [20,21] PhC waveguides.

Nevertheless, for the vast majority of photonic structures, the design principles for an optical diode seem to conflict on one important point. To increase the structure's sensitivity to the direction of incidence, one needs to increase the spatial asymmetry of the structure. However, to increase the maximum transmission at a resonance peak, the structure should remain symmetric. It was once believed that only symmetric multilayers can exhibit theoretically perfect transmission resonances (PTRs) [22–24] and that PTRs are explicitly related to mirror symmetry [25]. Further studies revealed that perfect transmission is rare but possible in asymmetric multilayers. Examples based on periodic [26], Fibonacci [27], and Thue-Morse [28] geometry were given. In a series of recent works, Grigoriev and Biancalana [28,29] report optical diode action based on PTRs in Thue-Morse multilayers. However, such structures typically need to consist of many layers due to relatively weak spatial asymmetry and field enhancement, increasing their sensitivity to the detrimental effects of material absorption and fabrication imperfections. Besides, quasiperiodic structures possess a very rich variety of resonant modes, not all of which lend themselves to straightforward studies. Although there has been definite progress in analytical treatment of nonlinear resonances in Thue-Morse multilayers [29], the overall picture remains complicated.

In our recent work [30], it was confirmed that mirror symmetry is sufficient but by no means necessary to design multilayers with PTRs. It was shown that structures combining perfect transmission and highly asymmetric light

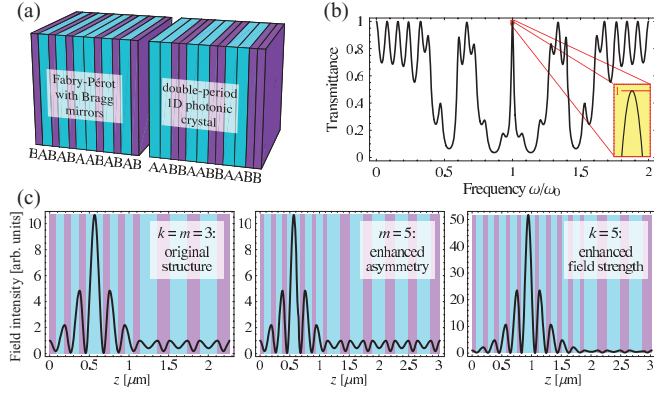*szhukov@physics.utoronto.ca
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FIG. 1. (Color online) (a) Design and (b) transmission spectrum of an FPPC structure $S^{(3,3)}$ as in Eq. (4), showing a PTR at ω_0 in the inset. (c) Asymmetric field distribution in structures $S^{(3,3)}$, $S^{(3,5)}$ (enhanced spatial asymmetry), and $S^{(5,3)}$ (enhanced localization strength) [30]. The materials are chosen as in Ref. [29] to be polydiacetylene (9-BCMU, $n_A = 1.55$, $\chi_A = 2.5 \times 10^{-5}$ cm^2/MW) and rutile (TiO$_2$, $n_B = 2.3$, $\chi_B \approx 0$). The thicknesses d_A and d_B are chosen according to Eq. (1).

localization at the resonant modes can readily be achieved in a simple Fabry-Perot-resonator–PhC (FPPC) geometry of the type $(BA)^k(AB)^k(AABB)^m$. Moreover, localization strength and asymmetry can be straightforwardly and independently controlled by changing k and m, respectively (see Fig. 1). It was envisioned that such structures would bring about an improved design of a nonlinear optical diode. However, an explicit investigation of this design in the nonlinear regime has not been performed.

In this paper, we investigate the nonlinear optical response of FPPC multilayers from the point of view of optical diode design. It is shown that FPPC structures are suitable for high-transmission and high-contrast unidirectional operation, resulting from combined contribution of PTRs and spatial asymmetry. A tradeoff between the strength of asymmetric response and the amount of reflection losses is established, so the best unidirectional operation is reported in a design where the PTR condition is slightly perturbed. Moreover, the effect of PTR restoration was observed where nonlinearity is seen to increase the maximum transmittance in a frustrated PTR back to unity. The optimized design exhibits optical diode action in the same input intensity range (around 10 MW/cm^2) but with less than half as many layers as a Thue-Morse structure reported in Refs. [28,29], owing to an increased localization strength in FPPC multilayers. By means of direct time-domain numerical simulations, optical diode action in the passive regime was demonstrated with more than 92% transmission. In the same parameter range, only pump-assisted or active operation was reported previously [18,28,29].

The paper is organized as follows. In Sec. II, the prerequisites needed for PTR formation in FPPC structures are briefly reviewed. In Sec. III, the nonlinear response of these structures is analyzed by using a nonlinear transfer matrix method. The role of asymmetry and PTRs in optical diode action is identified. It is found that perturbation of the PTR condition leads to a tradeoff between reflection losses and unidirectionality and that a proper structure design will cause

PTR restoration in the nonlinear regime. In Sec. IV, a direct numerical demonstration of optical diode action in FPPCs using time-domain simulations is provided. Finally, Sec. V summarizes the paper.

II. PERFECT TRANSMISSION RESONANCES IN MULTILAYERS

We consider binary multilayer structures built of two kinds of dielectric layers (labeled A and B) with thicknesses d_A and d_B, linear refractive indices n_A and n_B, and Kerr nonlinear coefficients χ_A and χ_B, respectively, located in a homogeneous dielectric medium with $n = n_0$. The building blocks A and B are assumed to be of the same optical thickness in the linear regime, so that

$$n_A d_A = n_B d_B = \pi c/(2\omega_0) = \lambda_0/4. \quad (1)$$

This equality is conventionally called the quarter-wave (QW) condition. It ensures that the transmission $T(\omega)$ and reflection $R(\omega)$ spectra for an arbitrary arrangement of A and B layers is periodic in frequency with period $2\omega_0$. An additional mirror symmetry is present in each period, so that [15,30]

$$\begin{aligned} T(\omega) &= T(\omega + 2\omega_0), \quad T(\omega_0 - \Delta\omega) = T(\omega_0 + \Delta\omega), \\ R(\omega) &= R(\omega + 2\omega_0), \quad R(\omega_0 - \Delta\omega) = R(\omega_0 + \Delta\omega). \end{aligned} \quad (2)$$

Thus all the spectral properties of a given QW multilayer structure, determined by its layer arrangement, are contained in the region $[0; \omega_0]$. Note that QW multilayers always have a PTR at even multiples of ω_0, so that $|T(2m\omega_0)| = 1$ exactly.

When two arbitrary multilayers S_1 and S_2 are stacked together to form a combined structure $S_1 S_2$, it is easy to relate its spectral properties to those of its constituents via Airy-like formulas at every frequency,

$$R_{S_1 S_2} = R_{S_1} + \frac{T_{S_1} R_{S_2} T_{\bar{S}_1}}{1 - R_{\bar{S}_1} R_{S_2}}, \quad T_{S_1 S_2} = \frac{T_{S_1} T_{S_2}}{1 - R_{\bar{S}_1} R_{S_2}}. \quad (3)$$

Here, $\bar{S}_1$ denotes the inversion of S_1, e.g., $\bar{S}_1 = BAABA$ for $S_1 = ABAAB$. Equations (3) can be used in a recurrent fashion with Fresnel formulas at dielectric interfaces acting as the initial conditions, giving rise to an analytical way of calculating $R(\omega)$ and $T(\omega)$ for any multilayer structure [30].

It can be seen from Eqs. (3) that $R_{S_1}(\omega) = R_{S_2}(\omega) = 0$ results in $R_{S_1 S_2}(\omega) = 0$ and $|T_{S_1 S_2}(\omega)| = 1$. That is, frequency-matched PTRs in the constituent structures always result in a PTR at the same frequency in the combined structure. It is known that both $S_1 = (BA)^k(AB)^k$ (a Fabry-Perot interferometer with a half-wave defect) and $S_2 = (AABB)^m$ (a 1D PhC with doubled period) have a PTR exactly at $\omega = \omega_0$. As a result, the combined FPPC structure

$$S^{(k,m)} \equiv S_1 S_2 = (BA)^k(AB)^k(AABB)^m \quad (4)$$

also has a PTR at $\omega = \omega_0$ [30]. As the light is strongly localized in S_1 (the Fabry-Perot part of the structure), the spatial field distribution in the resonant mode is highly asymmetric. Moreover, larger k enhances the strength of field localization, whereas larger m increases its spatial asymmetry [Fig. 1(c)], so they can both be controlled independently and straightforwardly. This makes the FPPC structures of Eq. (4) particularly attractive for a systematic study of unidirectional transmission involving a single-cavity resonant mode. In

what follows, we are going to analyze the nonlinear optical properties of $S^{(n,k)}$ at its PTR around ω_0.

III. NONLINEAR TRANSMISSION SPECTRA OF ASYMMETRIC MULTILAYERS

To investigate the optical properties of FPPC multilayers in the presence of Kerr nonlinearity, we assume that the refractive index varies with the field intensity I as

$$n_{A,B}^{(NL)}(z,t) = n_{A,B}[1 + \chi_{A,B}I(z,t)/2], \quad (5)$$

where $I = I(z,t)$ varies in both space and time, making the transmission spectrum intensity-dependent and potentially multistable [5,18,31]. To calculate it, we use the standard nonlinear transfer matrix method with layer subdivision [31]. (Note that more advanced methods have been introduced recently [29].) The example transmission spectra of $S^{(5,5)}$ are shown in Fig. 2. The PTR is seen to undergo characteristic resonance bending, in accordance with numerous earlier findings [9,18,19,28,29,31]. Obviously, the resonance bends more strongly as the input intensity increases, and the transmission spectra eventually become bistable [Fig. 2(b)] with hysteresis behavior clearly visible on an output versus input intensity diagram [Fig. 2(c)]. Note that a slight dependence on the direction of incidence can already be noticed in the hysteresis loop, although in $S^{(5,5)}$ the effect is too weak and requires very high input intensities.

From the FPPC design principles it is apparent how the changes in k and m should reflect themselves in nonlinear transmission spectra. Increasing k will increase both the resonant mode Q factor (making the resonance peak narrower) and the field enhancement factor (resulting in a stronger nonlinear interaction and hence a stronger resonance bending for the same input field intensity). Increasing m should enhance the asymmetry in the field distribution, so that the nonlinear transmission of the structure becomes more dependent on the direction on incidence. This is confirmed in Fig. 3. For moderate values of input intensity ($\leqslant 50\,\mathrm{MW/cm^2}$) asymmetric transmission starts to manifest itself for $k \geqslant 7$, becoming more pronounced with increasing m. It can be seen that, owing to direction-dependent asymmetry in resonance
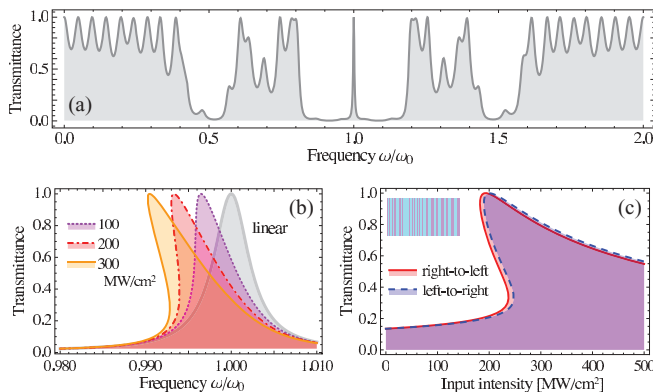
FIG. 2. (Color online) (a) Linear transmission spectrum, (b) nonlinear transmission spectrum around ω_0 showing PTR bending, and (c) input-output transmission hysteresis at $\omega = 0.9935\omega_0$ for the structure $S^{(5,5)}$.
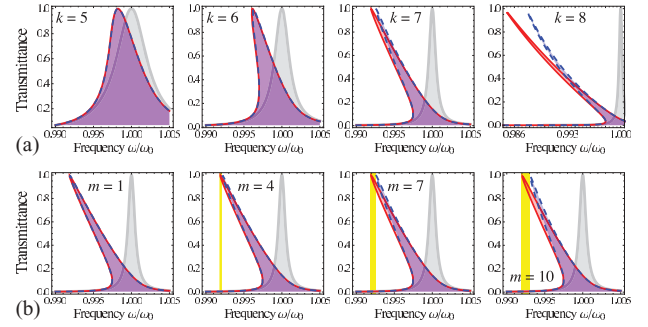
FIG. 3. (Color online) Nonlinear transmission spectra of (a) $S^{(k,7)}$ for $k = 5,6,7,8$ and (b) $S^{(7,m)}$ for $m = 1,4,7,10$. Red solid and blue dashed lines correspond to right-to-left and left-to-right propagation of light with an input intensity of 50 MW/cm². The light gray upright peak is the linear transmission spectrum. Regions of prospective unidirectional transmission are highlighted as light-yellow-shaded areas.

bending, there is a frequency range where a high-transmission state only exists for one direction of incidence [see Fig. 3(b)]. In this range, high-quality unidirectional transmission is expected.

Note in Fig. 3 that the maximum transmittance (T_{max}) in a bent PTR remains very close to unity despite the fact that Eq. (5) perturbs the QW condition (1) for $\chi \neq 0$. Hence the PTR condition (or, in fact, any recipe to provide a resonance with near-unity transmittance) is important to ensure that the reflection losses of an optical diode will remain low. To demonstrate that the diode performance is very sensitive to the structure design, we compare $S^{(7,7)}$ in Eq. (4) with its modification created by shifting the defect in its Fabry-Perot part, which can be expressed as

$$(BA)^{k-l}(AB)^{k+l}(AABB)^m. \quad (6)$$

The results are shown in Fig. 4. It is clearly seen that for the shifted defect ($l \neq 0$) the resonance is no longer a PTR and the linear transmittance comes nowhere near unity, resulting in poor T_{max} in the nonlinear regime as well. On the other hand, it can be seen that the asymmetry in transmission gets drastically enhanced. So, while the optical diode action severely suffers in terms of reflection losses, unidirectional transmission becomes far easier to achieve. The reason is that increasing the number of periods in a Bragg mirror greatly increases its quality, in turn increasing the amount of time it takes the light to tunnel through such a mirror into the Fabry-Perot defect mode. Hence, the difference of two periods in the $(BA)^{k-1}(AB)^{k+1}$ structure not only destroys the PTR condition but also creates
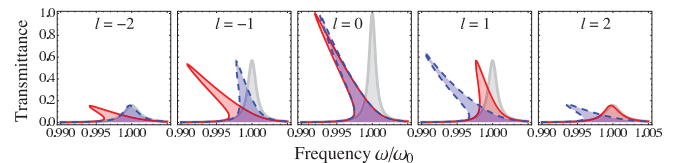
FIG. 4. (Color online) Nonlinear transmission spectra of the modified structure as of Eq. (6) for $k = 7$, $m = 7$, and $l = -2, \ldots, +2$. Red solid and blue dashed lines correspond to right-to-left and left-to-right propagation of light with an input intensity of 50 MW/cm².
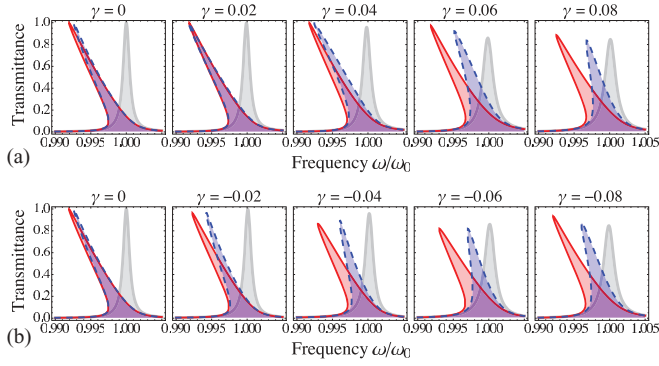
FIG. 5. (Color online) Nonlinear transmission spectra of the modified structure $S'^{(7,7)}$ as of Eq. (7) for (a) positive and (b) negative γ ranging between -0.08 and 0.08. Red solid and blue dashed lines correspond to to right-to-left and left-to-right propagation of light with an input intensity of $50 \, \text{MW/cm}^2$.

a much stronger asymmetric response than that introduced by the $(AABB)^m$ part. This is understandable because $(AABB)^m$ is free of internal reflections at ω_0, in contrast to $(BA)^{2l}$.

Therefore, it can be concluded that FPPCs feature a tradeoff between the maximum transmittance and unidirectionality. Hence it can be expected that optimum performance would
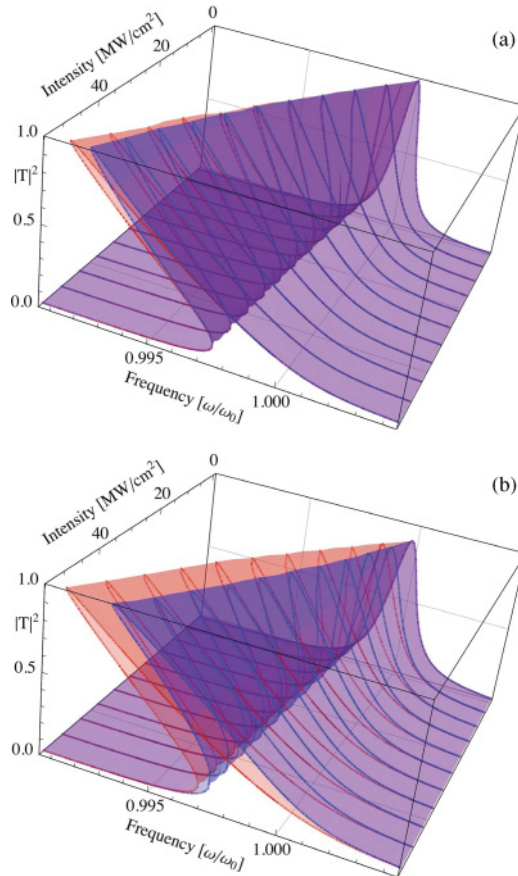

FIG. 6. (Color online) Nonlinear transmission spectra of (a) $S^{(7,7)}$ and (b) $S'^{(7,7)}$ with $\gamma = 0.05$, for input intensities up to $55 \, \text{MW/cm}^2$. Two semitransparent surfaces correspond to two different directions of light propagation.

be achieved with a slight perturbation of the PTR condition. Consider a structure

$$S'^{(k,m)} = (BA)^k (AB)^k (A'A'BB)^m, \qquad (7)$$

where A' denote the A layers with slightly changed optical thickness in the photonic crystal part, e.g., by

$$d_{A'} = (1 + \gamma) d_A. \qquad (8)$$

For small γ, Fig. 5 shows that the enhancement of unidirectionality more than makes up for a slight decrease in resonance quality. What is more, for $\gamma \simeq 0.04$ one can see that the nonlinear $T_{\max}$ becomes *closer* to unity compared to the linear regime, in the same way as was seen for $l = 1$ in Fig. 4. Hence, the $S'^{(k,m)}$ design not only combines the benefits of structures given by Eqs. (4) and (6) but also *restores* the PTR condition for a properly chosen γ. The reason is that the slight perturbation of the QW condition (1) by γ is compensated for by the nonlinear refractive index shift (5) for a certain value of input field intensity. Figure 6, comparing the three-dimensional nonlinear transmission spectra of $S'^{(7,7)}$ versus $S^{(7,7)}$, illustrates that the asymmetry is much more pronounced for the former case, while $T_{\max}$ remains close to unity in both structures. With the effect of PTR restoration taken into account, the $S'^{(7,7)}$ design is unambiguously superior in terms of the optical diode performance.

IV. TIME-DOMAIN SIMULATIONS OF OPTICAL DIODE ACTION

In this section, we demonstrate the unidirectional transmission and optical diode action in optimized FPPC structures as given by Eq. (7) by means of direct time-domain numerical simulations. We use the 1D Lax-Wendroff method [32] as implemented in Refs. [33,34], which is analogous to a commonly known Yee's finite-difference time-domain scheme.

In accordance with the guidelines of the previous sections, $S'^{(7,7)}$ with $\gamma = 0.05$ is examined as a model structure. As seen in Fig. 6(b), this structure features a maximum linear transmission of 91.2%. In the nonlinear regime, its right-to-left transmittance T_r increases toward unity due to the PTR restoration effect described above, while left-to-right transmittance T_l at the same frequency is low. The operating input intensity was chosen at a rather moderate value of $9.5 \, \text{MW/cm}^2$ in order to be able to work in the simple, passive regime. Higher input intensities ($> 20 \, \text{MW/cm}^2$), where the resonance peak gets sufficiently bent, make it increasingly difficult to excite the upper branch of the hysteresis loop by means of the incident wave alone. This can be overcome by using pump-assisted operation [18,21] or modulated incident wave [28,29], which is rather unfavorable for optical diode applications but may be promising for all-optical modulator designs.

The structure was discretized in the z direction with spatial mesh size $\Delta z = 5 \, \text{nm}$, which corresponds to 30–50 cells per layer. The time step was determined by the condition that the Courant number $\nu = 1$, so $\Delta t = 0.01667 \, \text{fs}$. Such parameters ensure that the effects of numerical dispersion can be neglected in our 1D calculations. Indeed, the test runs without nonlinearity confirm that the resonant frequency

$\omega_0 = 2\pi \times 12.161 \times 10^{14}$ Hz matches the results of linear transfer matrix calculations.

Unidirectional transmission is demonstrated by examining the steady-state response of the nonlinear multilayer to a continuous wave incident from either side of the structure. To simulate this, we use a quasimonochromatic wave packet with a rectangular envelope, long enough for the steady-state response to develop. The carrier frequency, determined by the input intensity values, was chosen at $\omega = 0.9982\omega_0$ or 12.1388×10^{14} Hz. To avoid numerical artifacts caused by abrupt onsets of the rectangular envelope, Gaussian-like transient excitations with a decay time of 0.03 ps were applied immediately before turning on and after turning off the rectangular quasimonochromatic pulse (at 1 and 37 ps, respectively).

The results are presented in Figs. 7(a) and 7(b). It is seen that right-to-left transmittance T_r eventually reaches 92.05%, slightly exceeding the maximum linear transmittance of the structure (91.2%), although the transient processes are seen to last for up to 15 ps. In the reverse direction, the transmittance T_l remains below 23%. The on-off contrast can be improved by increasing both the operating intensity and ω, which will also decrease the transient time in the right-to-left propagation, but

FIG. 7. (Color online) Results of FDTD simulations for passive diode action in an S$'^{(7,7)}$ structure for $I_0 = 9.5$ MW/cm^2 and $\omega = 0.9982\omega_0$: (a) with incident wave from the right and (b) with incident wave from the left. Solid lines indicate transmittance; dashed lines indicate reflectance. Blue (darker) color is for left-to-right propagation; red (lighter) color is for right-to-left propagation. In the background, the quasimonochromatic incident pulse is shown in light gray. The analytically derived operating point of the diode in (c) the intensity hysteresis loop and (d) the nonlinear transmission spectra is also presented, in the same form as Figs. 3–5.

this will decrease T_r. The maximum nonlinear correction to the refractive index, monitored in the middle of the Fabry-Perot cavity during entire simulation, does not exceed the values of 0.0085 (right-to-left propagation) and 0.003 (left-to-right propagation). These values are even lower than the estimation of 0.01 made in Ref. [29], so the structure is expected to remain stable for the chosen intensities.

For comparison, the operating regime of the proposed optical diode derived from the nonlinear transfer matrix method is presented in Figs. 7(c) and 7(d). The analytical calculation is seen to yield slightly better performance figures ($T_r = 93.5\%$, $T_l = 19.5\%$). These small discrepancies are attributed to spatial discretization present in both time-domain and nonlinear transfer matrix methods and can be seen as the effect of ~1%–2% structural disorder. Other than that, analytical and numerical results show very good agreement.

It is remarkable that the passive unidirectional transmission is observed at the lower-intensity "crest" of the hysteresis loop [see Fig. 7(c)] rather than at its higher-intensity "tail" as in earlier works [18]. Previously, only active or pump-assisted optical diode action was achieved in this regime [21,28,29].

Note, finally, that the demonstrated optical diode action occurs in the same input intensity range as in the recently reported Thue-Morse multilayers [28,29] but with the use of a structure less than half as thin and containing half as many layers (56 versus 128). This results from an increased field localization strength in FPPC structures. Another advantage of the FPPC design is that it allows one to purposely engineer a PTR-featuring resonant mode with desired properties, rather than rely on naturally occurring PTRs in photonic quasicrystals where not all resonant modes are suitable for unidirectional operation (see [29]). The operating intensities can be brought further down by increasing k, with a relatively insignificant increase in the number of layers. However, this will also increase the length of the transient response of the structure, effectively resulting in a tradeoff between energy efficiency and maximum attainable bandwidth when such an optical diode is used in communication systems.
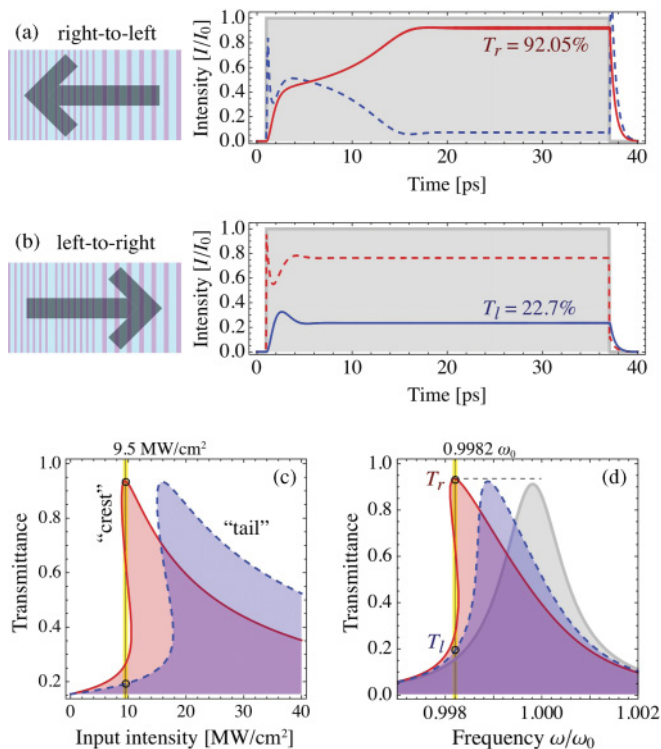
V. CONCLUSIONS AND OUTLOOK

In summary, we have theoretically investigated the optical properties of asymmetric Kerr-nonlinear multilayers with perfect transmission resonances. Using the nonlinear transfer matrix method, it is found that FPPC structures of the type $(BA)^k(AB)^k(AABB)^m$ exhibit both pronounced unidirectionality and high transmission, which makes these structures suitable for nonlinear optical diode action in the passive regime with low reflection losses. A tradeoff is found between the maximum transmission and unidirectionality, subject to tuning by slightly perturbing the PTR condition. An effect of PTR restoration is observed in perturbed FPPC structures. Theoretical predictions are confirmed in direct time-domain numerical simulations, yielding more than 92% transmission for the input intensity of <10 MW/cm^2. This value exceeds the linear maximum transmittance of 91.2%, further confirming the PTR restoration effect. A passive optical diode regime was demonstrated where only pump-assisted or active operation was reported previously [18,28,29], and the proposed geometry offers the same performance as recently

reported Thue-Morse multilayers [28,29] but with less than half as many layers.

The results obtained can also be viewed as a systematic investigation of a single photonic-multilayer resonant cavity in the nonlinear regime. They can be used as a starting point for investigating more sophisticated multilayer geometries combining spatial asymmetry and high transmission. For example, recent studies report that coupled-cavity resonances in multiple-defect PhCs [35] and photonic quasicrystals [29] have very different character of nonlinear bending and different properties of unidirectional transmission, compared to single-cavity resonances. To examine PTRs created by multiple Fabry-Perot elements coupled in an asymmetric fashion would therefore be a very interesting extension of the principles derived in the present work.

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