Optical Signal Processing Using Nonlinear Distributed Feedback Structures

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***Abstract*—We analyze the optical signal processing functionality of periodic structures consisting of alternating layers of materials possessing opposite Kerr nonlinearities. By elaborating an analytical model and employing numerical simulations, we explore the performance of proposed passive optical limiters and switches. We prove that the proposed limiters provide true limiting by clamping the transmitted intensity at a level which is independent of the incident intensity. We explore the response of optical switches for signal and pump beams having the same and different frequencies. We describe and quantify the performance of the proposed structures in the realization of all-optical OR gates and optical hard-limiters. In addition, we prove that, for fabrication errors as large as 10%, qualitative device functionality remains, with performance only modestly degraded.**

***Index Terms*—Electromagnetic scattering by periodic structures, optical limiters, optical propagation in nonlinear media, optical signal processing, optical switches.**

I. Introduction

OPTICAL limiters and switches provide a prospective basis for optical signal processing [1]–[10]. They can be used to filter, shape, and multiplex optical pulses and to limit the optical power [5]. Devices based on optical limiting and switching find application in ultrahigh-speed networks [11] and in specialized high-speed processors such as data and signal regenerators and encryptors [5]. Passive optical limiters are also commonly used as protective devices [12]–[15].

Ideally, the limiter should have a transmittance equal to one for low-intensity radiation. The transmittance should decrease with increasing intensity to the point that the transmitted intensity is clamped at a maximum acceptable level [16].

Depending on the application, passive optical limiters and switches are required to be either broad-band or narrowly spectrally discriminating. It is often desirable, especially in wavelength division multiplexing (WDM) systems, for a device to act only on a limited spectral range of light. It is then necessary that the limiter or switch should not affect the transmittance of the rest of the spectrum. On the other hand, since the spectral diversity of lasers in use is increasing, fixed-line spectral filters cannot offer complete protection of the optical components [12]. Thus, in the case of sensor protection, broad-band limiting is required.

A reliable optical limiter or switch must be resistant to optical damage [12], [17]. The nonlinear material responsible for limiting or switching action must not degrade when subjected to the high-intensity light on which it is operating. Additionally, the limiter or switch should be stable in the working environment. Thus, it should attach firmly to the sensor it is to protect and not be affected by motion [12].

Among the most commonly used passive optical limiters and switches are devices based on total internal reflection, self-focusing, self-defocusing, two-photon absorption, and photorefractive beam fanning [13], [14], [17]–[19]. Devices based on total internal reflection are very sensitive to alignment [17]. Self-focusing and two-photon absorption rely on the absorption of the incoming radiation and, as such, are vulnerable to damage of the nonlinear material [13], [14], [17], [19]. In self-defocusing limiters, only part of the transverse cross section of the light beam or pulse is transmitted. This leads to an output signal with a different transverse intensity profile than the incident pulse, which is often undesirable in optical signal processing [17]. In photorefractive beam fanning, the transmitted beam may lose its spatial and temporal coherence. In addition, high intensity weakens the photorefractive abilities of all known materials [17].

Given the vast usefulness of passive optical limiters and switches in optical signal processing and the inadequacy of the presently available solutions, we propose herein a technique that fulfills simultaneously each of the requirements described above. In this work, we explore the basic mechanisms of our approach and describe its applications.

The devices we model in this work rely upon the mechanism of nonlinear reflection rather than absorption of light. They are much less susceptible to damage than absorption-based devices. Since the proposed limiters and switches are composed of multilayer structures, they are relatively easy to fabricate into any desired shape or to attach to any kind or form of surface. Once attached, such devices will not be affected by motion of the sensor they are protecting. The limiters and switches we propose can be designed to be either highly wavelength-selective or to exhibit their properties over a broad range of wavelengths.

We provide herein the solutions to coupled-mode equations for the case of a one-dimensional (1-D) periodic medium illuminated with radiation at resonance. The medium is composed of layers with an identical linear refractive index and alternating opposite Kerr coefficients. We have obtained analytical expressions which aid us in obtaining physical insight into device operation and allow us to relate the response of the device to its structural and material parameters (average refractive index, Kerr coefficient, and number of periods). We have investigated potential uses in optical signal processing of the proposed limiters and switches.

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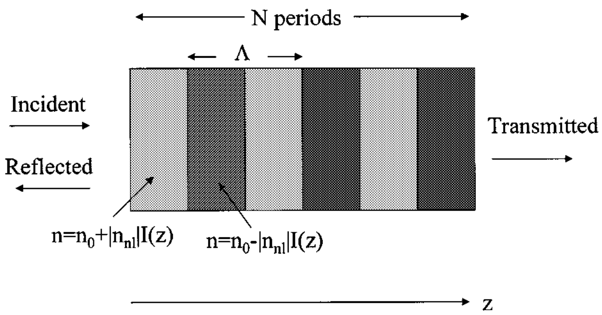


Fig. 1. Structures consisting of $2N$ alternating layers of materials with an identical linear refractive index and opposite Kerr coefficients.

We have restricted our analysis in this work to the case of a 1-D periodic nonlinear model system. A vast array of further device opportunities arise in the context of periodic three-dimensional (3-D) media. Such structures have already been realized through techniques of mesoscopic self-organization both in inorganic [20] and organic [21] materials. Either system lends itself to the selective inclusion of materials with fast Kerr-type nonlinearities of opposite signs. Limiters which are angularly as well as spectrally broad-band can be realized in these regular media. Signal-processing elements rooted not simply in 1-D nonlinear distributed reflection, but implementing nonlinear diffraction of signals—mediated by the set of available reciprocal photonic lattice vectors—can be envisioned.

II. Theoretical Model

The structures analyzed are shown in Fig. 1. They consist of alternating layers of materials, each one possessing a Kerr nonlinearity. The index of refraction of such a material can be expressed as [22], [23]

$$n = n_0 + n_{nl} I \tag{1}$$

where n_0 is the linear part, n_{nl} is the nonlinear intensity-dependent part, and I is the local intensity of light in the medium. The coefficient n_{nl} can be either positive or negative [3], [24]. Thus, depending on the sign of n_{nl}, the index of refraction of the given material can either increase or decrease as the intensity is increased. We analyze structures whose layer thicknesses are chosen to achieve the quarter-wave condition for an average index of refraction of 1.5 at frequency 3×10^{14} Hz ($\lambda_0 = 1\ \mu$m).

In order to obtain an analytical expression for the evolution of forward and backward propagating waves inside the structure, we use the coupled-mode formalism for the case of a nonlinear periodic medium [23], [25]. Applying these equations to our structures, we obtained coupled-mode equations under the following conditions: negligible absorption, the same linear index of refraction of the two materials, and opposite nonlinear Kerr coefficients:

$$\frac{dA_1(z)}{dz} = -\frac{\omega}{c}\frac{2n_{n1}}{\pi}\left(|A_1(z)|^2 + |A_2(z)|^2\right)A_2(z) \cdot e^{i((2\omega n_0/c)-(2\pi/\Lambda))z} \tag{2}$$

$$\frac{dA_2(z)}{dz} = -\frac{\omega}{c}\frac{2n_{nl}}{\pi}\left(|A_1(z)|^2 + |A_2(z)|^2\right)A_1(z) \cdot e^{-i((2\omega n_0/c)-(2\pi/\Lambda))z} \tag{3}$$

where A_1 and A_2 are the coefficients of the forward and backward propagating waves, respectively, ω is the frequency of the radiation, c is the speed of light in vacuum, k is the wavenumber of light, and Λ is the period of the grating. We have employed the slowly varying envelope approximation [22] in obtaining (2) and (3).

We solve at resonance $(2\omega n_0/c = 2\pi/\Lambda)$ (2) and (3) for $A_1(z)$ and $A_2(z)$ with the help of *Mathematica*. Two boundary conditions were specified, both at position $z = L$, where L is the length of the structure: $A_2(L) = 0$, i.e., that no radiation is incident on the structure from the right; and $A(L) = A_{1\text{out}}$. We obtain (4), shown at the bottom of the page, for the envelope of the forward-propagating wave in terms of the transmitted intensity ($I_{\text{out}} = |A_{1\text{out}}|^2$).

Taking the squared modulus of (4) yields the following expression for the evolution of the intensity of the forward-propagating wave across the structure:

$$I(z) = \left|\frac{1+\cos\left(\dfrac{4I_{\text{out}}n_{nl}(L-z)}{\Lambda n_0}\right)}{2\cos\left(\dfrac{4I_{\text{out}}n_{nl}(L-z)}{\Lambda n_0}\right)}\right| I_{\text{out}}. \tag{5}$$

Solving (5) for $z = 0$ gives the following relation between the transmitted and incident intensity:

$$I_{\text{in}} = \frac{1}{2}\left|\frac{1}{\cos\left(\dfrac{4I_{\text{out}}}{a}\right)} + 1\right| I_{\text{out}} \tag{6}$$

where $a = n_0/Nn_{nl}$ and $N = L/\Lambda$ is the number of periods.

Equation (5) gives I_{in} as a periodic function of I_{out}. Only solutions from the first period of this function are physically

$$A_1(z) = \sqrt{\frac{1 + 2\exp\left(\dfrac{-4iI_{\text{out}}n_{nl}(L-z)}{\Lambda n_0}\right) + \exp\left(\dfrac{-8iI_{\text{out}}n_{nl}(L-z)}{\Lambda n_0}\right)}{2\left(1+\exp\left(\dfrac{-8iI_{\text{out}}n_{nl}(L-z)}{\Lambda n_0}\right)\right)}}\, A_{1\text{out}} \tag{4}$$

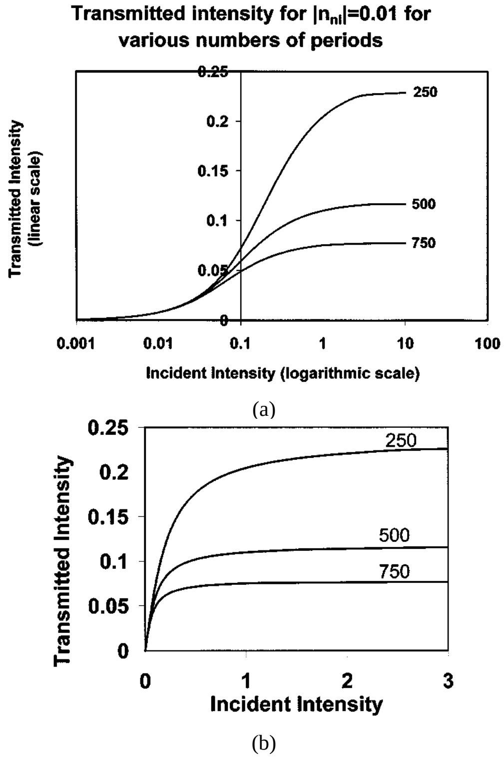


Fig. 2. (a) Limiting behavior of the proposed structures. This semi-logarithmic graph shows transmitted intensity as a function of incident intensity for structure with $n_{nl} = |0.01|$ for various numbers of periods. This plot illustrates the transition between low and high incident intensities as well as the saturation to a limiting value. Transmittance of the signal beam decreases with the increasing pump intensity and eventually approaches zero for high values of $I_{\rm pump}$. (b) A linear plot response for small values of incident intensity. All of the devices clamp the transmitted intensity to a limiting value.

possible—the remaining solutions imply a transmitted intensity larger than the incident intensity. The limiting value of $I_{\rm out}$ therefore occurs when

$$I_{\rm Limiting} = \frac{\pi}{8}\,\frac{n_0}{Nn_{nl}}. \tag{7}$$

As our numerical results (discussed below) confirm, (7) gives the highest value of the intensity that can escape the far side of the limiter. The result constitutes an analytical proof of true, or ideal, limiting action: transmitted intensity can be guaranteed to lie below a sensor-safe value for arbitrarily intense incident radiation.

III. Results and Discussion

With the help of analytical formulas presented above and numerical solutions of to coupled equations (2) and (3), we proceed to explore potential uses of the proposed structures in optical signal processing. We propose all-optical limiters, switches, OR gates, and optical hard-limiters based on our generic structure. We present elsewhere [26] an in-depth explanation of the physical processes responsible for the limiting behavior of the proposed devices.

In Fig. 2, we show on linear and semi-logarithmic plots the transmitted intensity as a function of incident intensity for various numbers of periods. The structures analyzed are made of materials with the linear index of refraction of 1.5 and opposite Kerr coefficients of magnitude 0.01. These graphs were based on (6). Here and in the rest of this paper, we use normalized intensity in units reciprocal to those of n_{nl}. The incident light was assumed to be resonant with the periodicity of the structure. In these plots, the transmitted intensity is seen to approach asymptotically a specific value determined by structural parameters. The value to which the intensity saturates is given by (7). This feature of true optical limiting is desired of passive optical limiters [16].

A figure of merit for the limiters is the Dynamic Range (DR). This quantity is defined as the ratio of the low-intensity transmission (T_L) to the high-intensity transmission (T_H), measured at the highest energies employed (DR $= T_L/T_H$) [16]. The analytical expressions derived predict the transmission of the proposed structures to approach zero as the incident intensity is sufficiently increased. Thus, there is no theoretical limit to the DR of our devices.

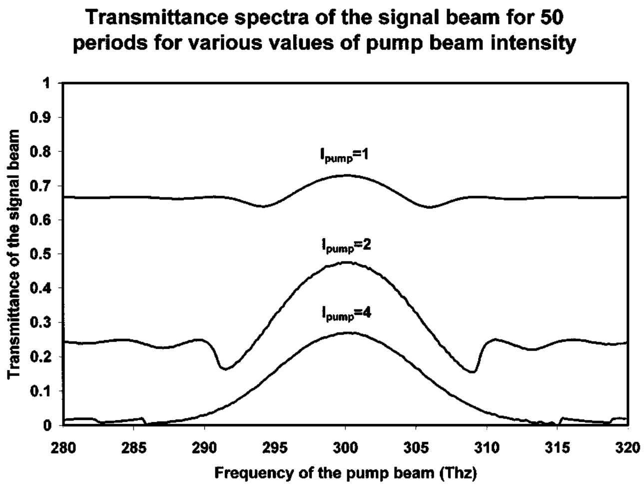
Realization of the proposed limiters using materials having opposite Kerr characteristics ensures saturation of the transmitted intensity to the limiting value. The center of the stopband is then fixed at the desired frequency, regardless of the incident intensity. Otherwise, a multilayer structure may display multistability [1], [27]–[32]. In contrast with the structures proposed herein, multistable structures generally do not exhibit saturation of the transmitted intensity to limiting value and may undergo chaotic behavior [28].

In an optical switch, the increasing intensity of the pump beam is used to lower the transmittance seen by a signal beam [6]. In order to distinguish the pump and signal beam at the output of the structure, it may be desirable to use beams of different frequencies. To analyze such cases, we use numerical simulation.

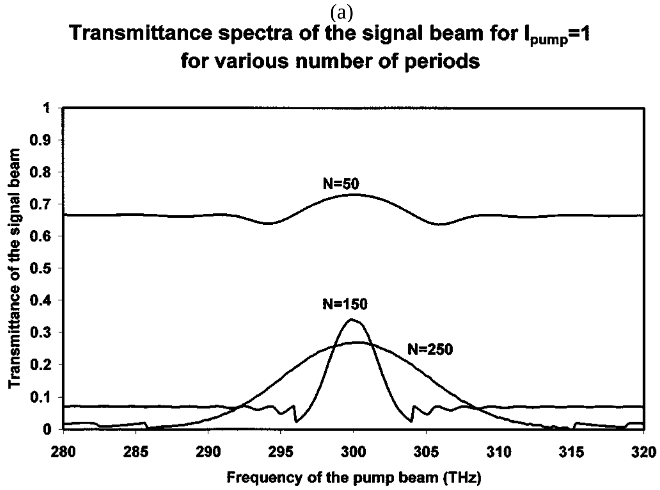
We show in Fig. 3(a) and (b) the results of these simulations. In both (a) and (b), the structures analyzed have refractive indices as in Fig. 2. We consider a signal beam having on-resonance frequency 3×10^{14} Hz. The low-intensity signal does not perturb the characteristics of the grating. The frequency of the pump beam is varied from 2.8×10^{14} Hz to 3.2×10^{14} Hz. In Fig. 6, we keep the number of periods constant at 50 and obtain transmittance spectra of the signal beam for pump intensities of 1, 2, and 4. In Fig. 7, we keep the pump beam intensity fixed at 1 and vary the number of periods (50, 150, and 250).

It is seen in Fig. 3(a) and (b) that the highest transmittance of the signal beam occurs when the frequency of the pump beam approaches the structural resonance of the periodic medium. As the frequency of the pump beam moves off resonance, the transmittance of the signal beam oscillates, eventually saturating far from resonance. If the pump beam is far beyond the resonant frequency, its transmittance is very close to one. The intensity of the pump beam is then constant throughout the structure; a flat Bragg grating is formed. Thus, the signal beam, which is on-resonance with the periodicity of this structure, is substantially blocked.

If, on the other hand, the pump beam is close to resonance, its intensity decays quickly and the refractive indices of only the layers at the beginning of the structure are strongly affected; the signal does not see a strong Bragg grating throughout the entire structure. The lowest value of the transmittance of the



(a)



(b)

Fig. 3. (a) Demonstration of switching capability. Transmittance of the signal beam as a function of the frequency of the pump beam. The structures analyzed have refractive indices as in Figs. 2–5. The signal beam was assumed to have an on-resonance frequency of 3×10^{14} Hz and a constant intensity of 0.1. The frequency of the pump beam was varied from 2.8×10^{14} Hz to 3.2×10^{14} Hz. The number of periods is kept constant at 50 and the intensity of the signal beam takes values of 1, 2, and 4. As the intensity of the pump beam is increased, the transmittance of the signal beam decreases. The transmittance of the signal beam is maximum when the pump beam is on resonance. (b) Probe beam intensity kept constant at 1 and number of periods varied (50, 150, and 250).

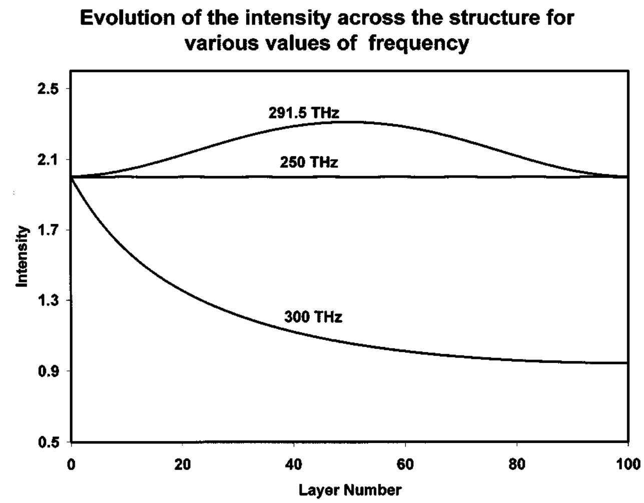


Fig. 4. Probe beam intensity across the structure of 50 periods for frequencies 250, 291.5, and 300 THz.

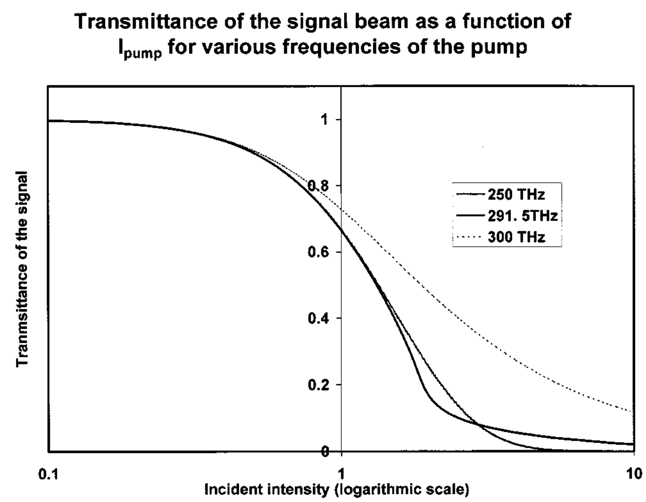


Fig. 5. Transmittance of signal beam as a function of the pump beam intensity. This plot demonstrates how $I_{\rm pump}$ alters the transmittance of the signal beam depending on the frequency (250, 291.5, and 300 THz).

signal beam takes place at the first minimum of the transmittance spectra. At this point, the intensity of the pump beam inside the structure is higher than the incident intensity. This phenomenon is well known in nonlinear Fabry–Perot etalons [30]. In our device, it yields a grating with a stronger effect on the signal beam than the flat Bragg grating which results form a pump beam far off the resonance. We plot in Fig. 4 the evolution of the intensity across the 50-period structure for $|n_{nl}| = 0.01$, $n_0 = 1.5$, and $I_{\rm pump} = 2$. The curves presented correspond to $I_{\rm pump}$ at 250 THz (far from resonance), 291.5 THz (at the first minimum), and 300 THz (structural resonance).

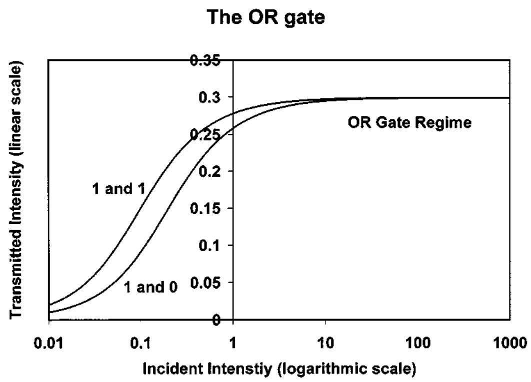
We show in Fig. 5 the transmittance of the signal beam as a function of $I_{\rm pump}$ for the same structure as in Fig. 4 for the same three frequencies. As $I_{\rm pump}$ is increased, the positions of the minima shift away from the fundamental maximum. The effective stopband grows wider and eventually encompasses the frequencies considered.

The nonlinear distributed Bragg gratings that we propose may also be used as OR gates or hard-optical limiters. If two beams are incident on the device and one is of sufficiently high intensity, the transmitted intensity will approach the limiting value (6). This situation corresponds to the input logic state (0,1) or (1,0) and an output of 1. If both of the beams are of large intensities, the transmitted intensity will approach the $I_{\rm Limiting}$ even more closely. We illustrate this OR gate behavior in Fig. 6.

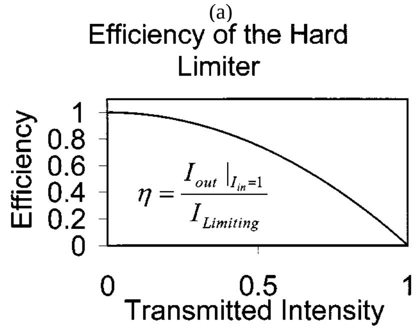
In an optical hard-limiter, the output is constant for input greater than a threshold value and 0 otherwise [11], [33]. In order to estimate the quality of the proposed hard-limiters, we introduce a general expression for the efficiency of hard limiters

$$\eta = \frac{I_{\rm out}|_{I_{\rm in}=1}}{I_{\rm Limiting}}. \tag{9}$$

We plot the efficiency for $I_{\rm in} = 1$ as a function of $I_{\rm out}$ in Fig. 6(b). The curve provides a guideline in the design tradeoff between hard-limiters ideality and output power.



(a)



(b)

Fig. 6. (a) OR gate. For high intensity, (0,1) and (1,1) input signals result in nearly the same output. (b) The predicted efficiency of the proposed hard-limiters as a function of the transmitted intensity for $I_{\rm in} = 1$.

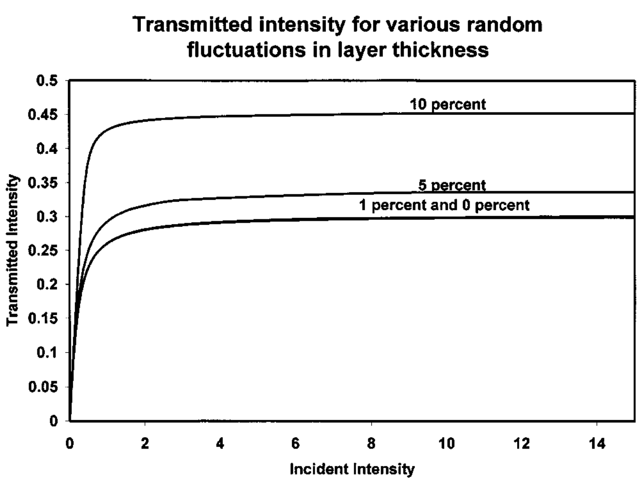


Fig. 7. Transmitted intensity as a function of incident intensity for the structure with the same parameters as in Figs. 2 and 3. The thickness of the layers was allowed to vary 1, 5, and 10% from their quarter-wave value. For 1% deviation there is no detectable difference in the response of the perturbed device and the ideal one.

In addition to presenting potential uses of the proposed structures in signal processing, we analyze the sensitivity of the proposed devices to fabrication errors. We simulate the response of structures with built-in random fluctuations in the layer thicknesses. Keeping all other parameters fixed, we allow the thicknesses to be uniformly distributed over a predefined range. In Fig. 7, we show the transmitted intensity as a function of the incident intensity for the structure with the same average parameters as in Figs. 2 and 3. Layer thicknesses were allowed to vary 1%, 5%, and 10% from their quarter-wave value. For 1% deviation, there is no detectable difference in the responses of the imperfect device and the ideal device. Even in devices with a larger degree of imperfection (5% and 10% fluctuations), the transmitted intensity saturates to some limiting value. Thus, though the quantitative performance of the device is affected by the fabrication errors, the device maintains its most important qualitative function.

IV. Conclusions

The structures which we have proposed herein are suitable for realization of devices with applications in optical signal processing. We have derived a number of analytical relationships that describe the response characteristics of the proposed devices in terms of the structural and material parameters. Materials with large Kerr coefficients and response times on of the order of picoseconds are available and possess low absorption coefficients, which justifies a purely dispersive treatment of the problem [1], [3], [24], [35]–[38]. Aided by the analytical expressions derived and numerical simulations employed, we have proven our structures to exhibit true liming behavior. We have also shown that these structures can be used as optical switches, OR gates, and hard-optical limiters. Finally, we have demonstrated that the proposed devices would maintain key qualitative behavior even with substantial fabrication errors.

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